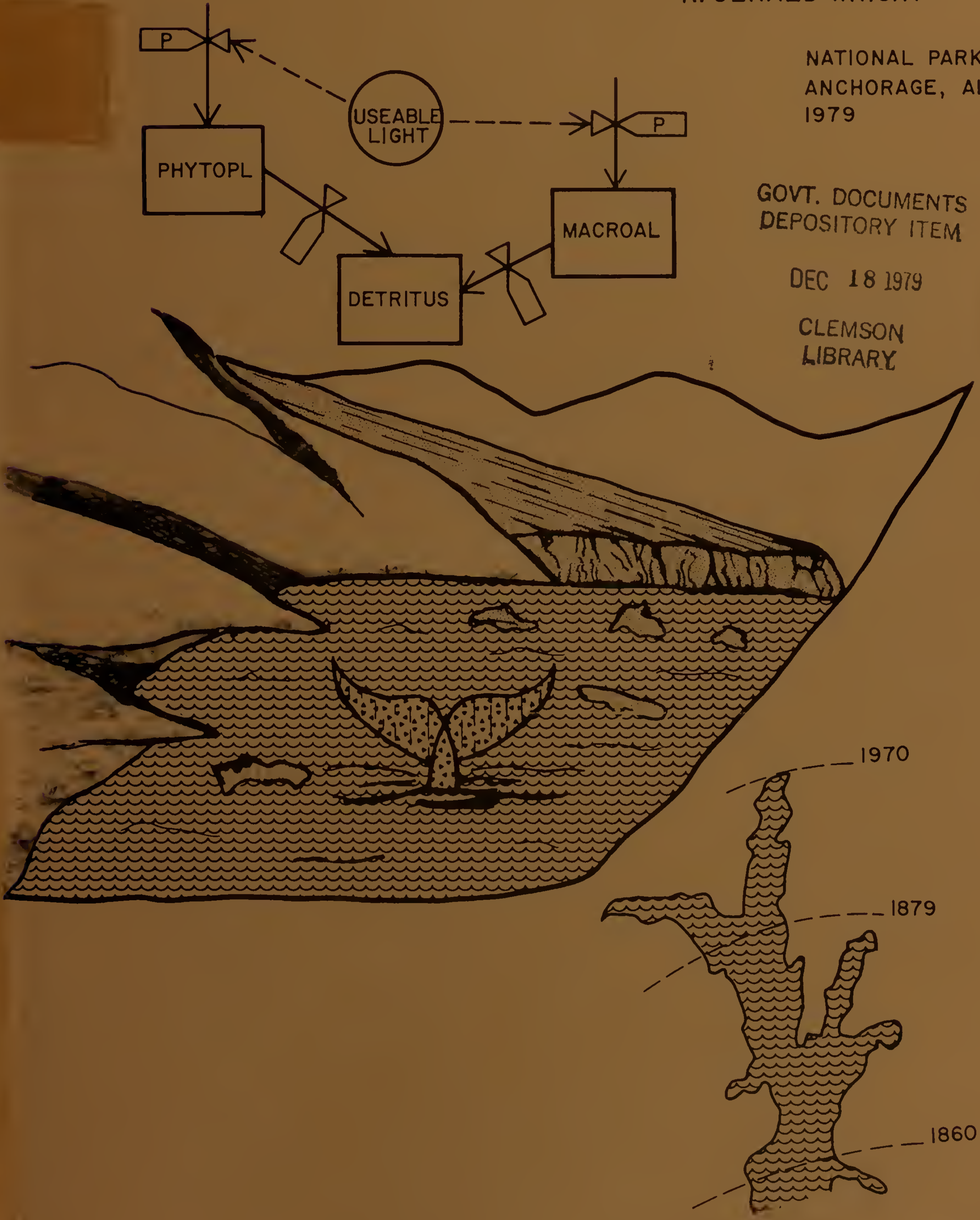
I 29.2: G 45/4

THE GLACIER BAY MARINE ECOSYSTEM
A CONCEPTUAL ECOLOGICAL MODEL

LYNNE ZEITLIN HALE
R. GERALD WRIGHT

NATIONAL PARK SERVICE
ANCHORAGE, ALASKA
1979

GOVT. DOCUMENTS
DEPOSITORY ITEM
DEC 18 1979
CLEMSON
LIBRARY



GLACIER BAY MARINE ECOSYSTEM

A CONCEPTUAL ECOLOGICAL MODEL

April 1979

Lynne Zeitlin Hale
R. Gerald Wright

U.S. Department of Interior
National Park Service
Anchorage Area Office

ACKNOWLEDGEMENTS

Many individuals contributed to this project. The entire Glacier Bay Monument staff shared their thoughts and knowledge about Glacier Bay with us. We want to give special thanks to Greg Streveler, Research Biologist; Bruce Paige, Park Naturalist; and Tom Ritter, Superintendent, for their support and help. Fred Dean of the Cooperative Park Studies Unit of the University of Alaska generously provided office space for LZH. His many helpful discussions during the project were also appreciated. The Jurasz family shared their vast knowledge and love of Glacier Bay with us; and that has been invaluable. Ross Kavanagh provided a particularly thorough review of the first draft and offered many valuable suggestions. The individuals listed in Appendix I provided ideas, and in many cases unpublished data about Glacier Bay which greatly facilitated the project. Ellen Lewis drafted the report's figures and Hedy Ahluwalia suffered with us through many drafts and typed the manuscript.

TABLE OF CONTENTS

Page

List of Figures....................v
List of Tables....................viii

INTRODUCTION....................1

THE GLACIER BAY SYSTEM....................3

THE CONCEPTUAL MODEL....................8
- The Summer Model....................10
- The Winter Model....................13
- Seasonal Trends....................13
- Upper Glacier Bay Model....................13

SECTION I A SUMMARY OF INFORMATION ON THE PHYSICAL ENVIRONMENT OF GLACIER BAY....................18
- Climate....................19
  - Wind....................19
  - Solar Radiation....................22
  - Ice....................22
- Marine Geology....................24
  - Glacial Retreat....................24
  - The Shoreline....................27
  - Bathymetry....................27
  - Bedrock Structure, Relief and Sediment Thickness...28
  - Surface Sediments....................28
  - Suspended Sediments....................33
- Water Mass Characteristics....................38
  - Water Circulation....................39
  - Tides and Tidal Currents....................41
  - Bathymetry....................42
  - Deep Water Renewal....................42
  - Freshwater Input....................44
  - Glacial Fjords....................46
  - Turbid Outwash Fjords....................46
  - Water Transparency....................46
  - Inorganic Nutrients....................48
- Habitat Types....................54
  - Upper/Lower Glacier Bay....................54
  - Inlet Type....................56
  - Intertidal Zone....................58

Page

SECTION II A SUMMARY OF INFORMATION ON THE BIOLOGICAL ENVIRONMENT OF GLACIER BAY....62
- Primary Producers....63
  - Primary Producer Model....63
  - Phytoplankton....65
  - Macroalgae....69
- Zooplankton....71
  - Zooplankton Submodel....71
  - Species Composition....73
- Benthos....75
  - Benthos Submodel....75
  - Infauna....75
  - Epifauna....78
  - Relationship of Benthos to the Physical Environment....79
  - Distribution of Benthos in Glacier Bay....80
- Finfish....81
  - Finfish Submodel....81
  - Pelagic Fish....83
  - Demersal Fish....83
  - Anadromous Fish....84
- Marine Mammals....90
  - Harbor Seals....90
  - Humpback Whales....97
  - Killer Whales....102
  - Harbor Porpoise....102
- Birds....103
  - Bird Submodel....103
- Detritus....110
  - Detritus/Nutrient Regeneration Submodel....110
- Visitor Experience....113
  - Visitor Experience Submodel....113

SECTION III A SUMMARY OF INFORMATION ON MAJOR HUMAN ACTIVITIES AT GLACIER BAY....116
- Commercial Fishing....117
  - Finfish....117
  - Shellfish....126
  - Sportfishing....132
- Vessel and Aircraft Traffic....135
  - Types of Vessels and Aircraft....135
- Sewage Input....139
  - Sources of Sewage to Glacier Bay....139
- Mining....141

SECTION IV ANALYSES AND CONCLUSIONS....143
- Introduction....144
- Biological Research Needs....144

SECTION IV (CONT.) Page

Phytoplankton and Macroalgae Studies....................145
Zooplankton Studies....................146
Benthic Studies....................147
Fish Studies....................147
Mammal Studies....................148
Bird Studies....................149
Finfishing....................149
Crabbing....................153
Vessel and Aircraft Traffic....................153
Mining....................158

SUMMARY....................160

BIBLIOGRAPHY....................162

APPENDIX I: PEOPLE FROM WHOM VERBAL INFORMATION WAS OBTAINED....................171

APPENDIX II: CONTENTS OF DATA APPENDIX....................172

APPENDIX III: CONVENTIONS AND SYMBOLS USED IN THE MODEL DIAGRAMS....................174

APPENDIX IV: ABBREVIATIONS USED IN THE CONCEPTUAL ECOLOGICAL MODELS OF GLACIER BAY....................176

LIST OF FIGURES

Figure Page

1 Glacier Bay: Orientation Map....4

2 The Glacier Bay marine ecosystem: inputs/outputs....6

3 The major biological components of the Glacier Bay conceptual ecological model....9

4 Glacier Bay Ecological Model: Summer....11

5 Food Web diagram - Summer....12

6 Glacier Bay Ecological Model: Winter....14

7 Food Web diagram - Winter....15

8 Upper Glacier Bay Ecological Model: Summer....16

9 The wind direction distribution for Alder Site, Muir Inlet....21

10 Maximum Extent of winter pan ice in Glacier Bay....23

11 Position of glacier termini in Glacier Bay over the last 200 years....25

12 Marine surface sediment size and mineral composition....29

13 Queen Inlet bottom topography and surface sediment size....31

14 Size-frequency distribution of inlet valley floors, Queen Inlet....32

15 Optical transmission profiles at the northwest head of Queen Inlet....35

16 Mean seasonal profile of density anomoly in Muir Inlet....40

17 Depths of fjord sills in Glacier Bay, Icy Strait, Cross Sound and Chatham Strait....43

18 Estimated freshwater input to Glacier Bay....45

19 Nutrient concentration profiles in Glacier Bay and Icy Strait, July, 1967....51

Figure Page

20 Nutrient concentration profiles in upper Glacier Bay, May, 1967....53

21 Habitat types in Glacier Bay....55

22 Plant submodel....64

23 Zooplankton submodel....72

24 Benthos submodel....76

25 Fish submodel....82

26 Generalized life cycle of Halibut....87

27 Marine mammals submodel....91

28 Major harbor seal haul out sites in Glacier Bay....94

29 Habitat for humpback whales in Glacier Bay in 1976 and 1977....100

30 Bird submodel....106

31 Detritus/Nutrient regeneration submodel....111

32 Visitor experience submodel....114

33 Commercial fishing activity at Glacier Bay....118

34 Commercial fishing vessel visits to Glacier Bay, 1972-1977....119

35 International Pacific Halibut Commission regulatory and statistical areas in southeastern Alaska....121

36 Catch per unit effort in IHPC area 18 S-I and sub-area 182, 1958-1977....122

37 Salmon catch (by trolling gear) in A.D.F.&G. area 114, 1971-1976....125

38 Commercial Tanner, King and Dungeness crab catches in Glacier Bay, 1972-1977....127

39 Areas of exploration for and high abundance of pink shrimp, 1950-1960....131

40 Number of charter and private vessel using Glacier Bay, 1970-1977....134

Figure Page

41 A classification of vessels and aircraft....................137

42 Impacts of commercial fishing and crabbing on the biological system of Glacier Bay............................150

43 Impacts of commercial fishing and crabbing on the visitor experience...152

44 Impacts of vessel traffic on the biological system of Glacier Bay...155

45 Impacts of vessel traffic on the visitor experience..........157

LIST OF TABLES

Table | Page

1 Average monthly precipitation and maximum and minimum temperatures of Bartlett Cove....20

2 Physical characteristics of Glacier Bay's tributary inlets...57

3 Seasonal occurrence of common phytoplankton genera in Bartlett Cove, 1968-1969....67

4 Benthos infauna from Queen Inlet....77

5 Common animals taken by exploratory fishing drags....85

6 Trawl catch in Icy Strait....86

7 General life history features of the five species of Pacific salmon in Alaska....88

8 Harbor seal population estimates, 1972-1977....93

9 Natality estimates for harbor seals, 1975-1977....96

10 Humpback whale population estimate, 1976-1978....98

11 The seasonal occurrence of birds commonly found in Glacier Bay....104

12 Halibut catch by statistical sub-area, area, region and country, 1958-1977....123

13 Regional significance of the Glacier Bay crab catch, 1972-1977....129

14 General characteristics of the five important species of Alaskan shrimp....130

15 Number of visits by different vessel types to Glacier Bay, 1970-1977....136

INTRODUCTION

The concept that environmental systems, which are composed of living organisms interacting both with each other and the non-living environment, should be viewed holistically, rather than as a collection of unrelated objects, forms the foundation of the science of ecology. The use of descriptive and conceptual models to provide a framework for organizing knowledge about ecosystem components and processes is a well accepted research tool and communication device. Models employed in this way are simplifications of the real world. They attempt to illustrate only the essential portions of the ecosystem under study at a comprehensible level of detail. This type of organizational framework is generally termed a systems approach.

Conceptual models have the potential of being particularly useful to the National Park Service in its mission of planning, managing and interpreting huge, heterogeneous natural systems about which often little is known, but within which important management decisions must be made. A systems approach has been employed throughout this project -the development of a conceptual ecological model of Glacier Bay, the major fjord system in Glacier Bay National Monument. Through the models presented herein, we have attempted: 1) to organize and synthesize the available data; 2) to identify significant information gaps; 3) to delineate those ecological components and processes that appear to be most significant in Glacier Bay and thus should be most closely monitored and studied; and 4) to look at the pathways of potential impacts on the system.

The first section of the report gives an overview of the Glacier Bay marine system. A series of general conceptual models which illustrate major seasonal changes in the importance of the system's biological and physical components is presented. The following sections summarize what is known about Glacier Bay, beginning with the physical environment (Section II). The discussion of the biological components (Section III) is structured according to the same categories used in the general conceptual models. For each of these major compartments, conceptual submodels have been developed which summarize the available data and illustrate key biological and physical factors that interact to determine a compartment's biomass at any point in time. The concluding section of the report discusses future research needs in Glacier Bay, from both scientific and management perspectives.

A separate data appendix, referred to throughout the text, is available at the Glacier Bay National Monument library and the library of the Anchorage Area Office of the National Park Service. A listing of its contents is included in Appendix II of this report.

THE GLACIER BAY SYSTEM

Glacier Bay is located in Southeastern Alaska, at the northwestern end of the inside passage (Fig. 1). At present, Glacier Bay is approximately 15 hundred square kilometers in area and has 15 tributary inlets, 10 of which are also fjords. Four of these tributary fjords have tidewater glaciers, another five are best described as turbid outwash fjords and one, Tidal Inlet, no longer receives glacier meltwater.

Glacier Bay has had an exciting contemporary history. Two hundred years ago the entire bay was covered with ice. The pace of the ice's retreat since then has been astonishingly rapid, but variable. The result of this ice recession has been the creation of a spectacularly dynamic and complex fjord system.

Glacier Bay is not a homogeneous body of water, either in time or space. Successional processes following the most recent rapid deglaciation have resulted in the development of a gradient of biological communities of the lower Bay where the ice has been gone the longest to the less diverse communities found in the upper Bay. These biological differences are teamed with physical differences such as greater water clarity and more constant salinity in the lower Bay. The result is a gradual transition from a complex to a more simple ecosystem structure as one moves up Bay.

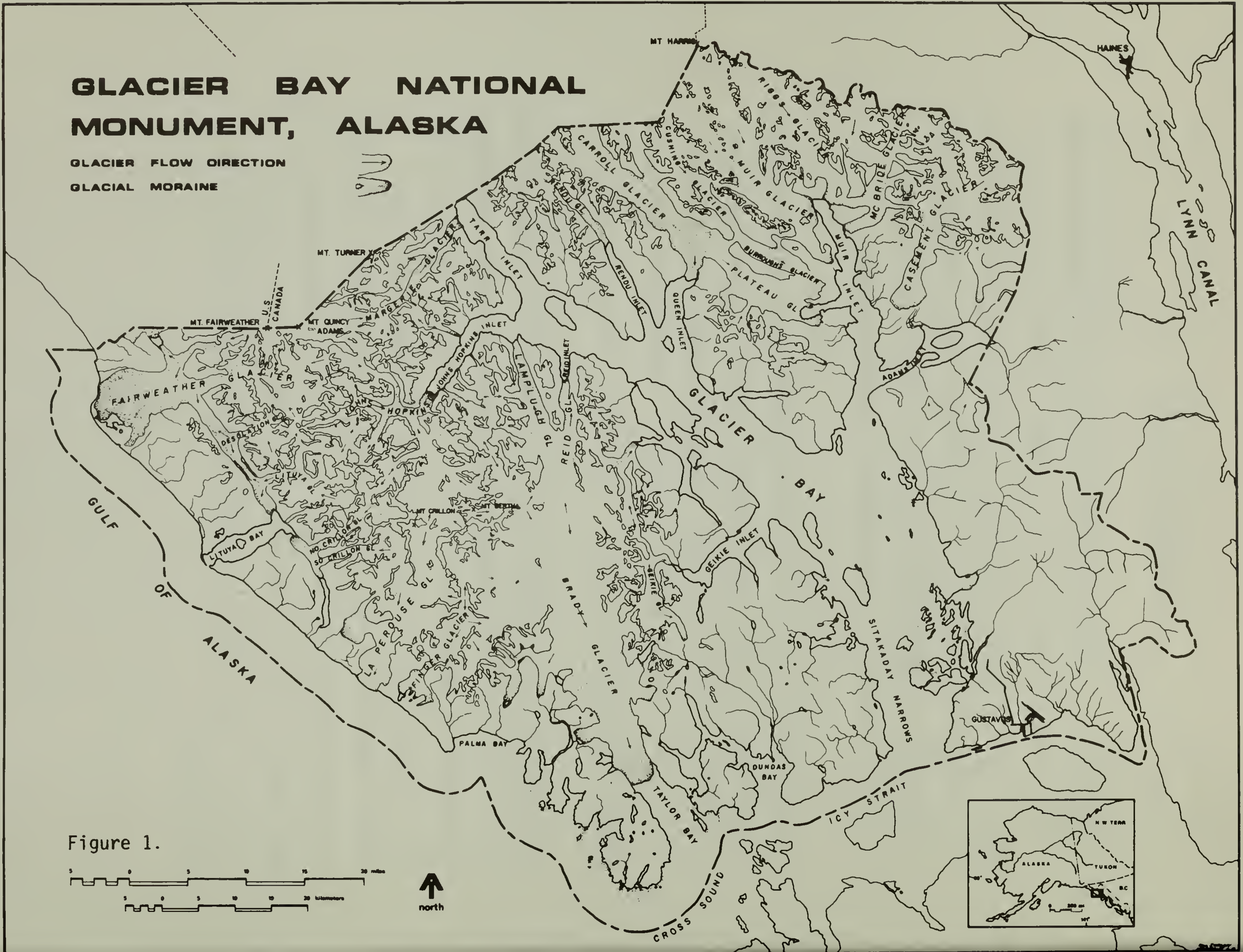

GLACIER BAY NATIONAL MONUMENT, ALASKA
GLACIER FLOW DIRECTION
GLACIAL MORAINE
MT HARRIS
HAINES
LYNN CANAL
RIGGS GLACIER
CUSHING GLACIER
MUIR GLACIER
MC BRIDE GLACIER
CASEMENT GLACIER
CARROLL GLACIER
RENDU GL
BURROUGHS GLACIER
PLATEAU GL
MUIR INLET
ADAMS INLET
TARR INLET
RENDU INLET
QUEEN INLET
MT. TURNER
U.S.
CANADA
MT. FAIRWEATHER
MT QUINCY ADAMS
MARGERIE GLACIER
JOHNS HOPKINS INLET
JOHNS HOPKINS
LAMPLUGH GL
REID INLET
REID GL
FAIRWEATHER GLACIER
DESOLATION
LITUYA GL
MT CRILLON
MT BERTHA
NO. CRILLON GL
SO. CRILLON GL
LITUYA BAY
LA PEROUSE GL
FINGER GLACIER
BRADY GLACIER
GEIKIE GL
GEIKIE INLET
GLACIER BAY
SITAKADAY NARROWS
GUSTAVUS
PALMA BAY
DUNDAS BAY
TAYLOR BAY
ICY STRAIT
CROSS SOUND
GULF OF ALASKA
N W TERR
ALASKA
YUKON
BC
north
5 0 5 10 15 20 miles
5 0 5 10 15 20 kilometers

Figure 1.

This study considers Glacier Bay as a system in that the Bay comprises a set of regularly interacting and interdependent components forming a unified whole (Odum 1971). Because this system is geographically well defined, it is theoretically possible to quantitatively assess the influences of surrounding lands and waters as exchanges (inputs and outputs to the system) across the geographic boundary. This makes Glacier Bay a near ideal subject for a modelling study.

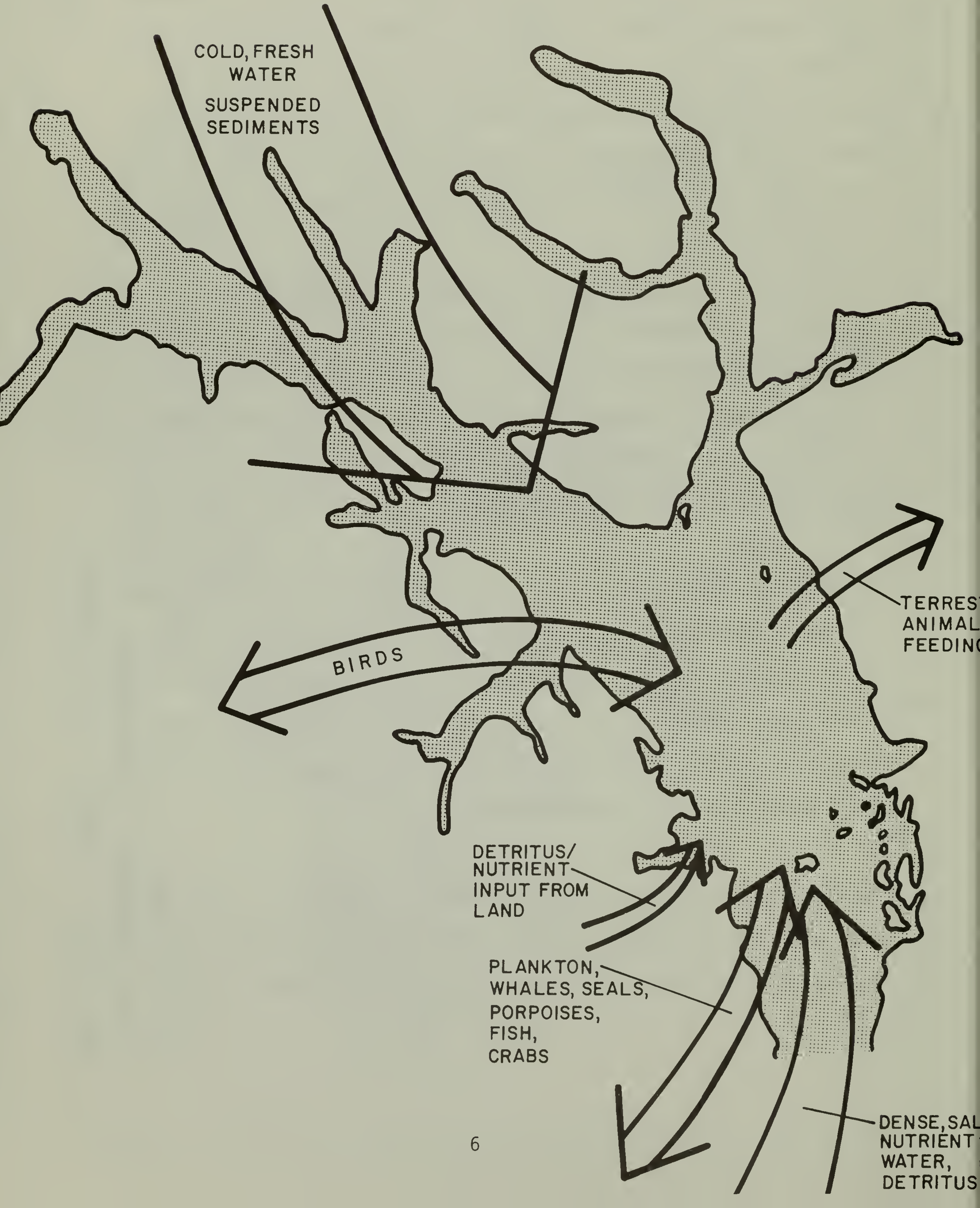
The principal exchanges across the geographic boundary are illustrated in Figure 2. Freshwater enters the system mainly in the form of glacial meltwater and precipitation, bringing sediment into the upper reaches of the Bay and organic material into the lower Bay. Marine waters from the Pacific Ocean enter Glacier Bay via Icy Strait. The waters in Icy Strait have their source both in Cross Sound and Chatham Strait.

Plankton are carried into and out of Glacier Bay with the tides. Inputs from the Pacific Ocean via Icy Strait include migratory fish, shellfish, marine mammals, and, through bottom water renewal, nutrient and possibly detritus-rich water. Birds freely enter and leave the Bay, and many terrestrial animals enter the geographic system by coming to the intertidal to feed, especially in the winter.

Changes and cycles are the unifying themes of Glacier Bay. There have been long-term successional changes relatively well studied on land but unstudied in the marine environment. There are pronounced seasonal

Figure 2. GLACIER BAY MARINE ECOSYSTEM

INPUTS/OUTPUTS



changes, of both physical and biological system components and processes, and the short daily changes brought about by the ebb and flow of the tide.

Like other Alaskan fjords, Glacier Bay is characterized by two distinct sets of oceanographic conditions over an annual cycle. There is a winter/spring homogeneous condition which begins to develop in November and is most pronounced in February. During this time, freshwater and sediment input are minimal and bottom water renewal from Icy Strait occurs. By June, a summer/fall heterogeneous condition, where fresh or brackish water overlies a warmer more saline layer, is well developed. This highly stratified condition remains through September. Sediment input during this period is very high, particularly in the upper tributary inlets.

Glacier Bay's biological cycles follow the physical cycles. With the onset of spring conditions there are marked increases in production and biomass. Much of the biomass increase comes from harbor seals that enter the bay to pup, and more migratory animals that move into Glacier Bay to feast on the temporarily abundant pelagic foods. The spring/summer migrants include the endangered humpback whale, large numbers of migratory birds, and all five Alaskan species of salmon.

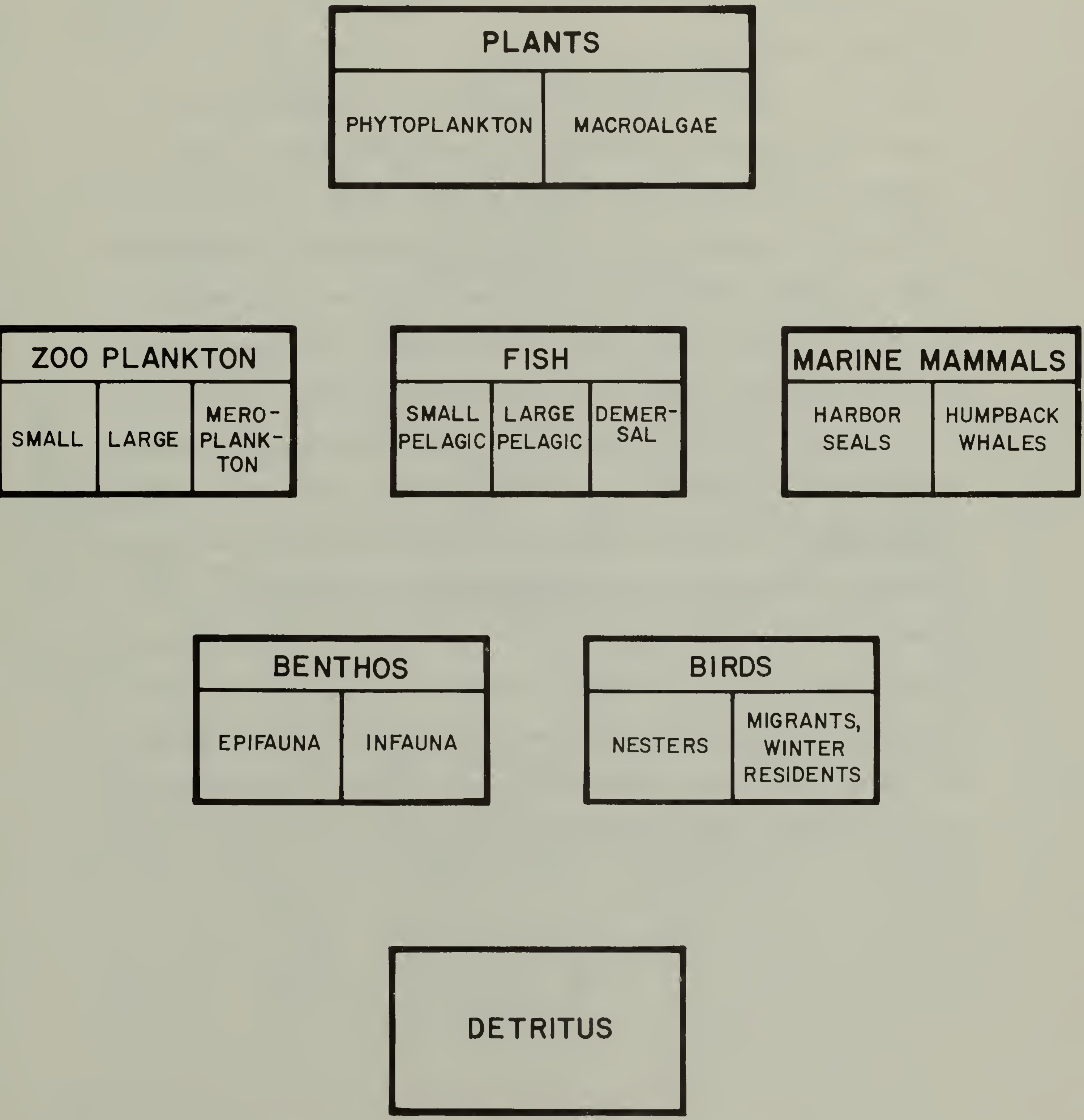
In winter conversely, a simpler structure prevails with a shift in energy pathways, lower production, and a lower species diversity and abundance.

THE CONCEPTUAL MODEL

We have tried to capture these representative characteristics of the Bay in conceptual, seasonally oriented models of the Glacier Bay marine ecosystem. In both models, the same major biological components as illustrated in Figure 3 are used. Five physical factors- solar radiation, glacial turbidity, nutrient concentrations in the euphotic zone, and the tides are also illustrated. The size of each box (representing a biological component) is important only in how it changes from season to season; the box size is not directly proportional to biomass. Unless otherwise indicated, the models shown are for Glacier Bay as a whole, however, it must be remembered as one moves up bay, certain species are found in smaller numbers or are entirely absent.

The starting point in the development of all models discussed in this report was the collection of all information available on Glacier Bay. This included data and observations from past and on-going research within Glacier Bay as well as research done in other Southeast Alaskan Fjords. Personal observations by many individuals interviewed by the senior author (see Appendix I), unpublished data, and inferences from the authors' general knowledge also figured significantly in the development of the conceptual models.

Figure 3. BIOLOGICAL COMPONENTS
GLACIER BAY CONCEPTUAL ECOLOGICAL MODEL



While these models serve as our working hypotheses on how the Glacier Bay marine system works, it must be emphasized that they are based on scanty data, the authors' understanding of how marine systems function, and, at times, our hunches.

The Summer Model

Figure 4 is a model of Glacier Bay in July and is representative of summer conditions. An illustrative diagram of this model is shown in Figure 5. The major build-up of phytoplankton which occurred earlier in the spring is now over. Zooplankton grazing has probably reduced phytoplankton biomass. Nutrient levels, while fairly low, are probably sufficient to support some photosynthesis; however, phytoplankton production may be light limited because of water turbidity. Zooplankton are now abundant with large zooplankton (euphausid) populations becoming significant as a food source. With seals on the pupping grounds and humpback whales in the bay, the marine mammal population is probably at a maximum. Southbound migrating birds (especially phallaropes) are already in the Bay in large numbers. The situation in July then is one of peak biomass, with a substantial proportion of this biomass being contributed by large, mostly migratory animals. These large consumers rely primarily on a well-developed pelagic food chain. From this point on, most of these temporary members of the Glacier Bay system start to leave.

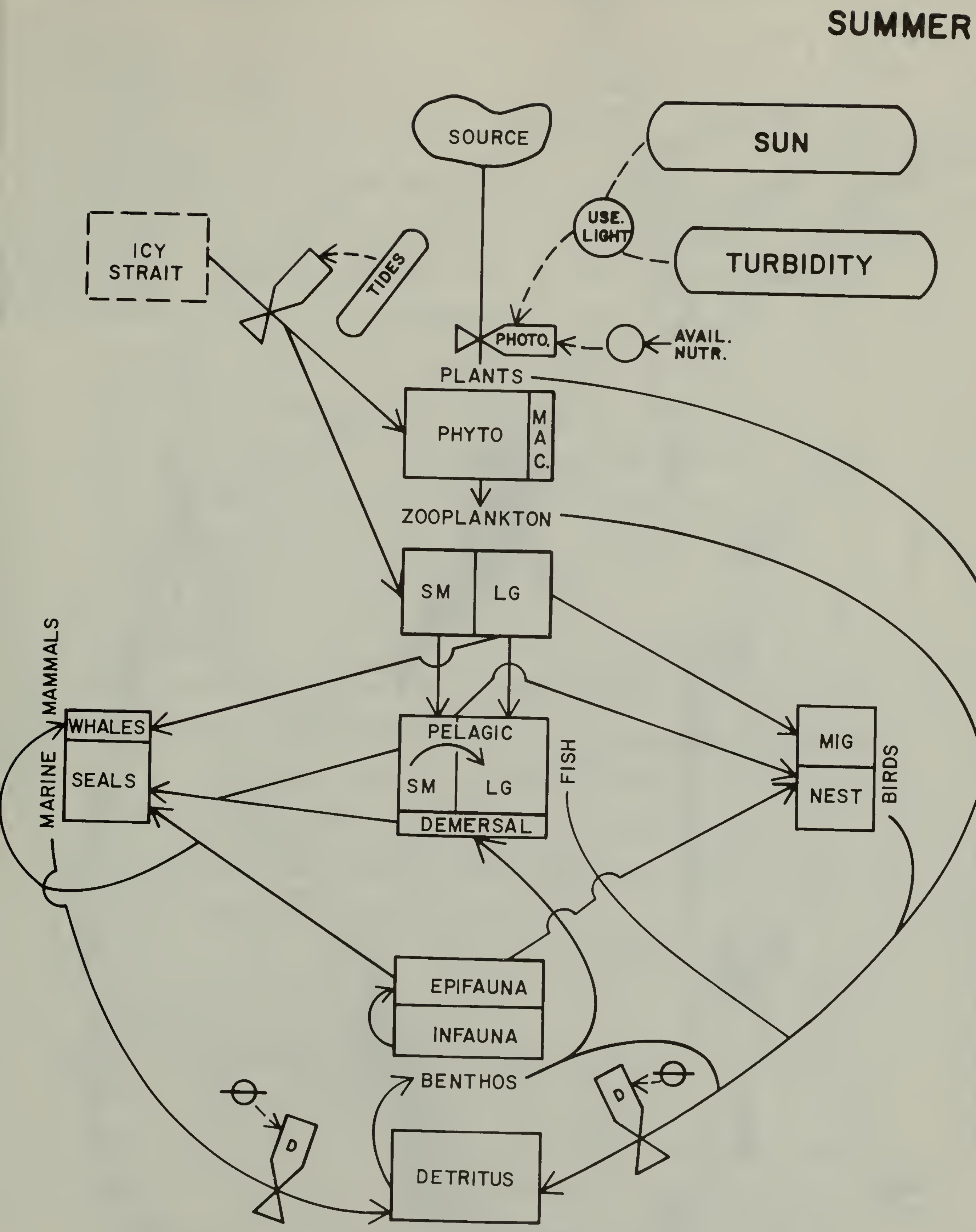
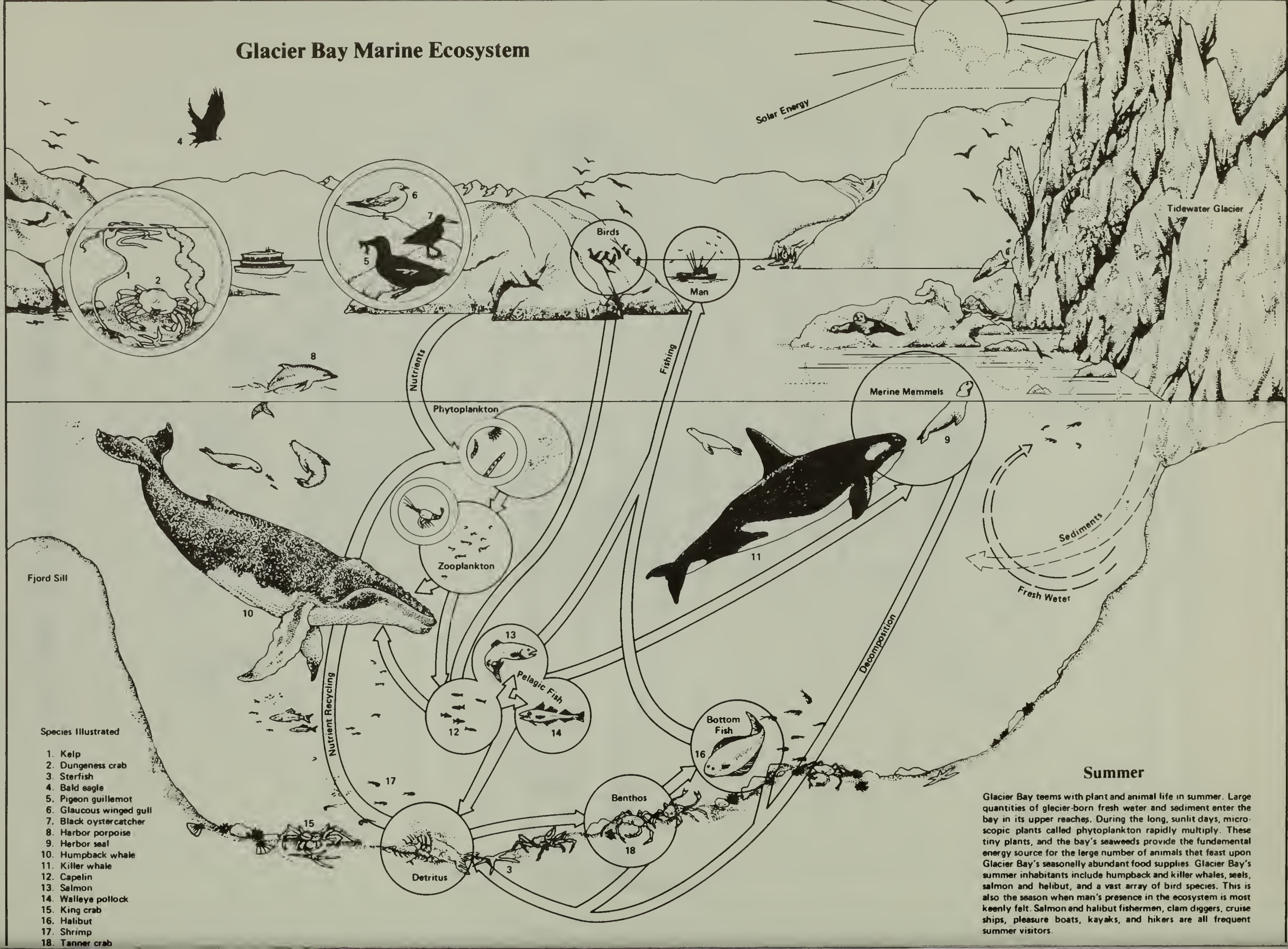


Figure 4. GLACIER BAY ECOLOGICAL MODEL

Glacier Bay Marine Ecosystem



Species Illustrated

1. Kelp
2. Dungeness crab
3. Starfish
4. Bald eagle
5. Pigeon guillemot
6. Glaucous winged gull
7. Black oystercatcher
8. Harbor porpoise
9. Harbor seal
10. Humpback whale
11. Killer whale
12. Capelin
13. Salmon
14. Walleye pollock
15. King crab
16. Halibut
17. Shrimp
18. Tanner crab

Summer

Glacier Bay teems with plant and animal life in summer. Large quantities of glacier-born fresh water and sediment enter the bay in its upper reaches. During the long, sunlit days, microscopic plants called phytoplankton rapidly multiply. These tiny plants, and the bay's seaweeds provide the fundamental energy source for the large number of animals that feast upon Glacier Bay's seasonally abundant food supplies. Glacier Bay's summer inhabitants include humpback and killer whales, seals, salmon and halibut, and a vast array of bird species. This is also the season when man's presence in the ecosystem is most keenly felt. Salmon and halibut fishermen, clam diggers, cruise ships, pleasure boats, kayaks, and hikers are all frequent summer visitors.

The Winter Model

In winter, the situation is quite different (Figs. 6 and 7). There are few plankton in the water and macroalgae, especially the small perennial kelps, probably account for the bulk of what little primary production occurs. Through bottom water renewal nutrient rich waters are brought into Glacier Bay. Fish populations are not known but are probably reduced, the humpback whales are gone and the seal population reduced to about 1300 individuals. The bird population is still substantial, however the majority of species present are common murres and diving ducks (principally old squaws), which feed on near bottom animals (especially shrimp) and scoters which largely feed on mussels.

Seasonal Trends

From these models it is possible to see a seasonal shift in food and energy pathways between the summer and winter systems. In summer there is a well developed pelagic system probably supported in large part by Glacier Bay's large late spring phytoplankton bloom. In the winter Glacier Bay shifts to a detritus-based system and a central role for the benthos, especially shrimp is suggested.

Upper Glacier Bay Model

The ecological system found in upper Glacier Bay during spring and summer is more simple than that for the Bay as a whole (Fig. 8). The Upper Bay summer system in many respects resembles the winter conceptual model for the entire Bay. Peak phytoplankton populations probably occur somewhat earlier in the upper inlets than the lower Bay, then become

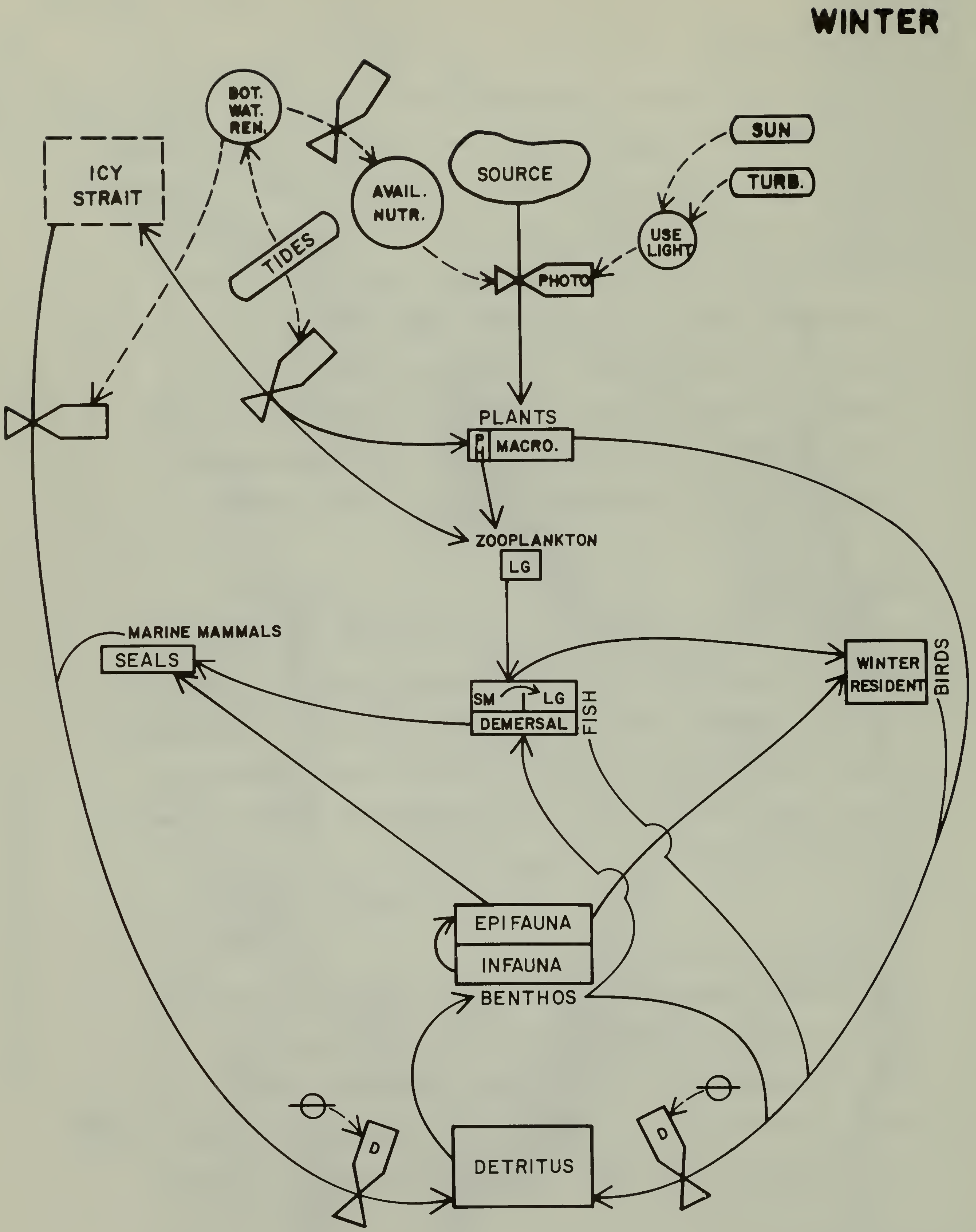
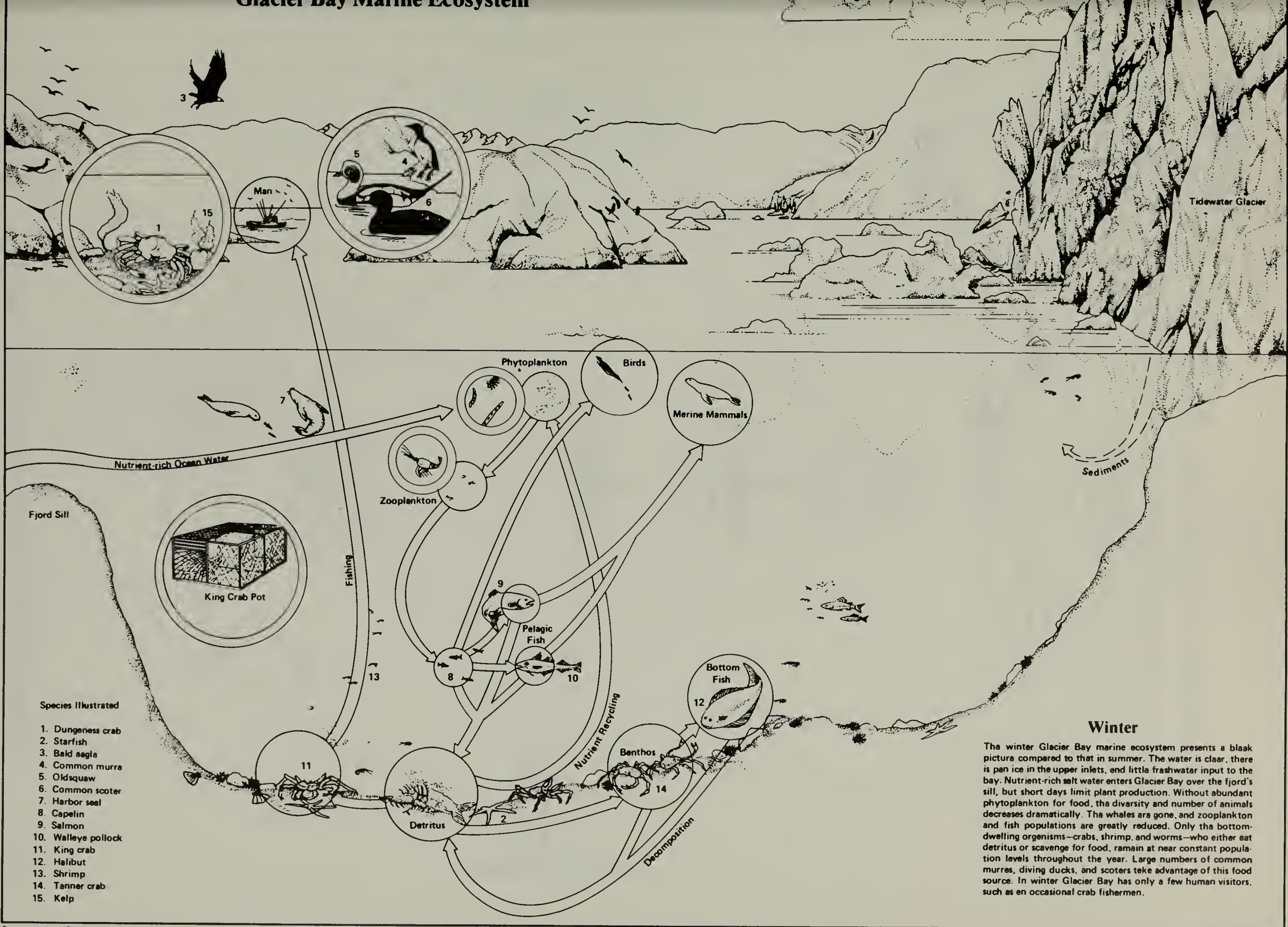


Figure 6. GLACIER BAY ECOLOGICAL MODEL

Glacier Bay Marine Ecosystem



Species Illustrated

1. Dungeness crab
2. Starfish
3. Bald eagle
4. Common murre
5. Oldsquaw
6. Common scoter
7. Harbor seal
8. Capelin
9. Salmon
10. Walleye pollock
11. King crab
12. Halibut
13. Shrimp
14. Tanner crab
15. Kelp

Winter

The winter Glacier Bay marine ecosystem presents a bleak picture compared to that in summer. The water is clear, there is pan ice in the upper inlets, and little freshwater input to the bay. Nutrient-rich salt water enters Glacier Bay over the fjord's sill, but short days limit plant production. Without abundant phytoplankton for food, the diversity and number of animals decreases dramatically. The whales are gone, and zooplankton and fish populations are greatly reduced. Only the bottom-dwelling organisms—crabs, shrimp, and worms—who either eat detritus or scavenge for food, remain at near constant population levels throughout the year. Large numbers of common murres, diving ducks, and scoters take advantage of this food source. In winter Glacier Bay has only a few human visitors, such as an occasional crab fishermen.

Prepared by Arctic Environmental Information and Data Center
for U.S. National Park Service 1979

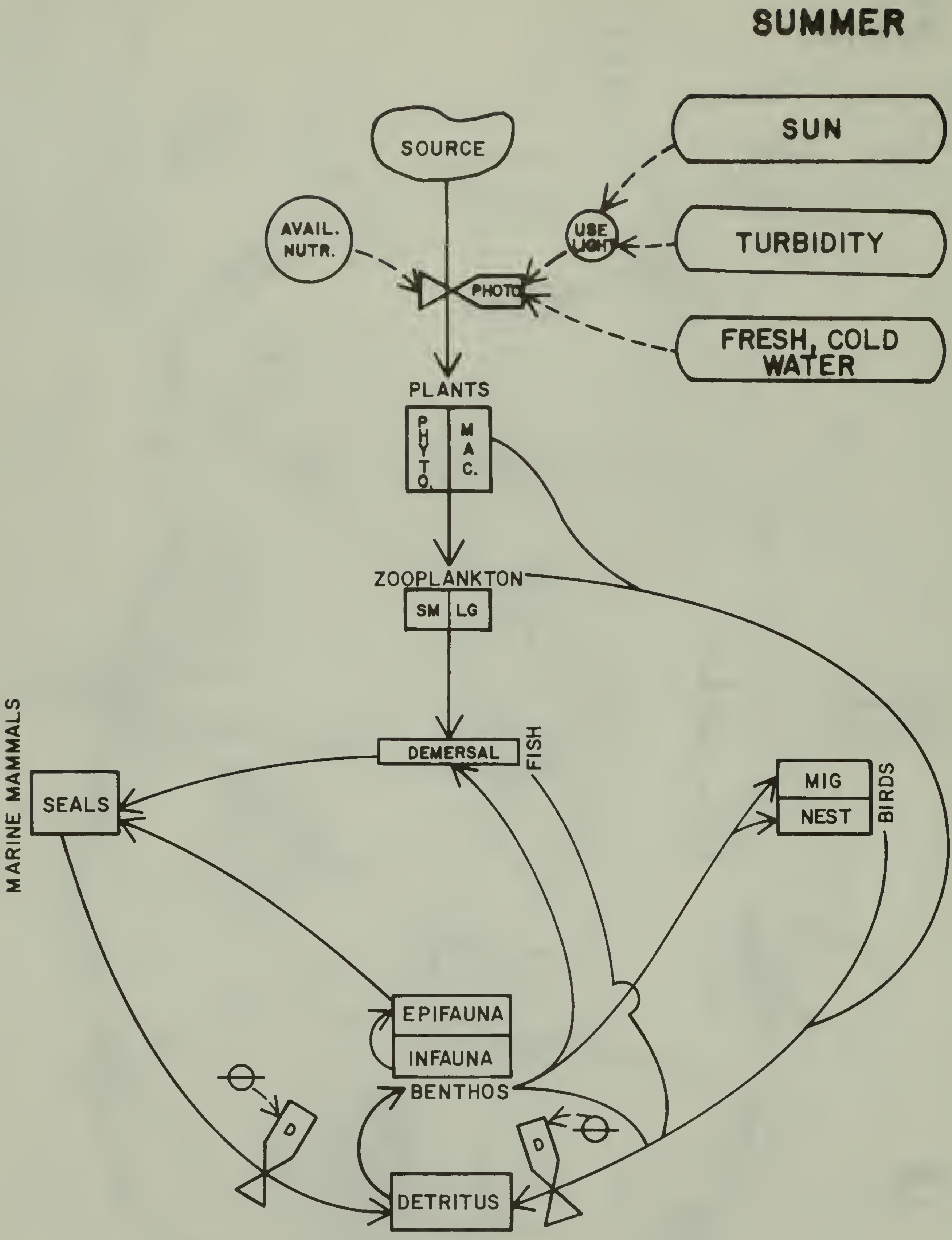


Figure 8. UPPER GLACIER BAY ECOLOGICAL MODEL

light limited. The other pelagic system components- zooplankton, fish and, with the exception of harbor seals, marine mammals are less abundant. Substantial shrimp and small tanner crab populations do occur. As in Glacier Bay as a whole for winter, the benthos appear to be a particularly important food source for other organisms. In winter, upper Glacier Bay probably more closely resembles the lower Bay.

SECTION I

A SUMMARY OF INFORMATION ON THE PHYSICAL ENVIRONMENT OF GLACIER BAY

CLIMATE

Cool summers, warm winters and abundant rainfall characterize Glacier Bay's climate. Maximum temperatures rarely exceed 24° C or drop below -23° C. Table 1a presents average monthly maximum and minimum temperatures at Bartlett Cove. Precipitation averages 75 inches per year at Bartlett Cove with March through July being the driest period and September and October being the wettest (Table 1b).

The climate of Glacier Bay National Monument is more completely described by Streveler and Paige (1971); however, it must be noted that the data available are scanty and climatic variations are noticeable even within Glacier Bay proper. Climatic data not included in that report will be discussed below.

Wind

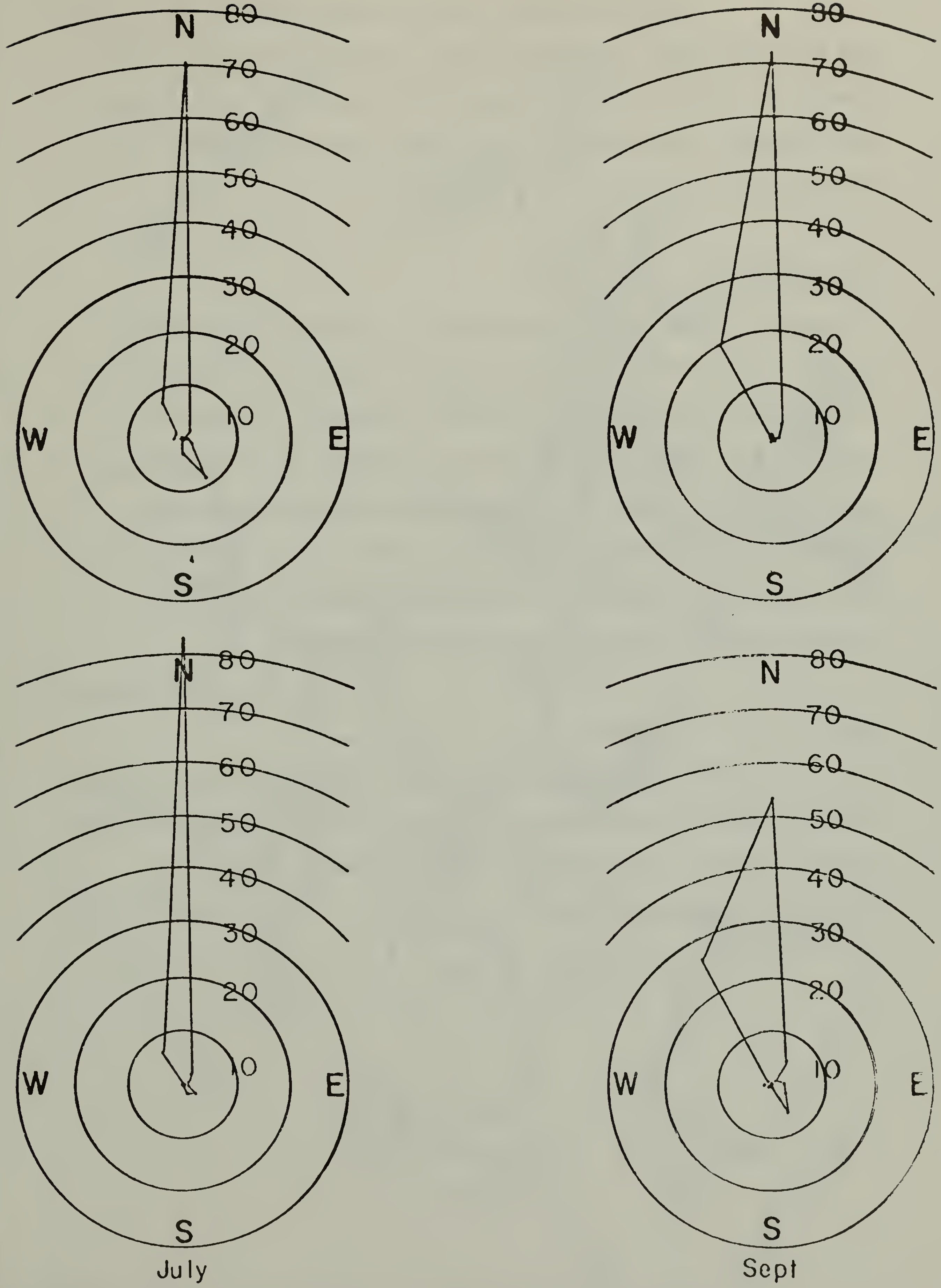
Wind is often an important mixing agent in the marine environment; its role in the Glacier Bay marine ecosystem is not known but is probably not significant. Synoptic wind measurements within the Monument have not been made. During recent summers Benson et al. (1977, 1978) collected wind data in Goose Cove, Muir Inlet. During both summers wind speeds were extremely low (about 4.4 mph) and blew principally from the north directly down inlet, following the Inlet's topography (Fig. 9). In September the wind started shifting to the west but data collection was not continued. During the summer, air temperature inversions frequently form over Glacier Bay. The combination of such temperature inversions

Table 1a. Average Monthly Maximum - Minimum Temperatures at Bartlett Cove (May, 1960 through 1968) adapted from Streveler and Paige (1971).

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Max.	-1	2	2.5	7	12	14	17	16.5	13	7.5	2.5	0
Min.	-5	-2.5	-2.5	0	4	7	8.5	8.5	6	3.5	-1.5	-4

Table 1b. Eight Year Average Monthly Precipitation (1961-1968) at Bartlett Cove. (Data are reported in inches)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Totals
Precip.	7.0	6.4	4.6	3.8	3.6	3.6	4.4	6.4	10.5	10.1	7.3	7.3	74.69
Snow	34.5	36.0	25.6	5.1	-	-	-	-	-	0.9	15.1	36.7	154.3



gure 9. Wind direction distribution for Alder Site, Muir Inlet.

and slow wind speeds, result in air flow in Muir Inlet which is slow, stable and probably laminar. During the fall and winter winds become much stronger, particularly in Tarr and Reid Inlets (Streveler, personal communication).

Solar Radiation

The amount of solar radiation available to a system places an upper limit on its productivity. Solar radiation available at the surface of Glacier Bay is not known. Pyrheliometer measurements were taken by Benson *et al*. (1978). Although June has the most hours of daylight, May, because it tends to have clearer skies, probably has the most sunlight reaching the Bay's surface. The number of days with clear skies, scattered clouds, broken clouds and overcast skies in June through September 1978 are shown in the data appendix.

Ice

Sea ice is seldom thick or extensive within Glacier Bay although pan ice usually forms at the heads of the tributary inlets and in sheltered and brackish locations. The maximum extent of winter ice coverage in Glacier Bay is shown in Figure 10.

MAXIMUM EXTENT WINTER PAN ICE

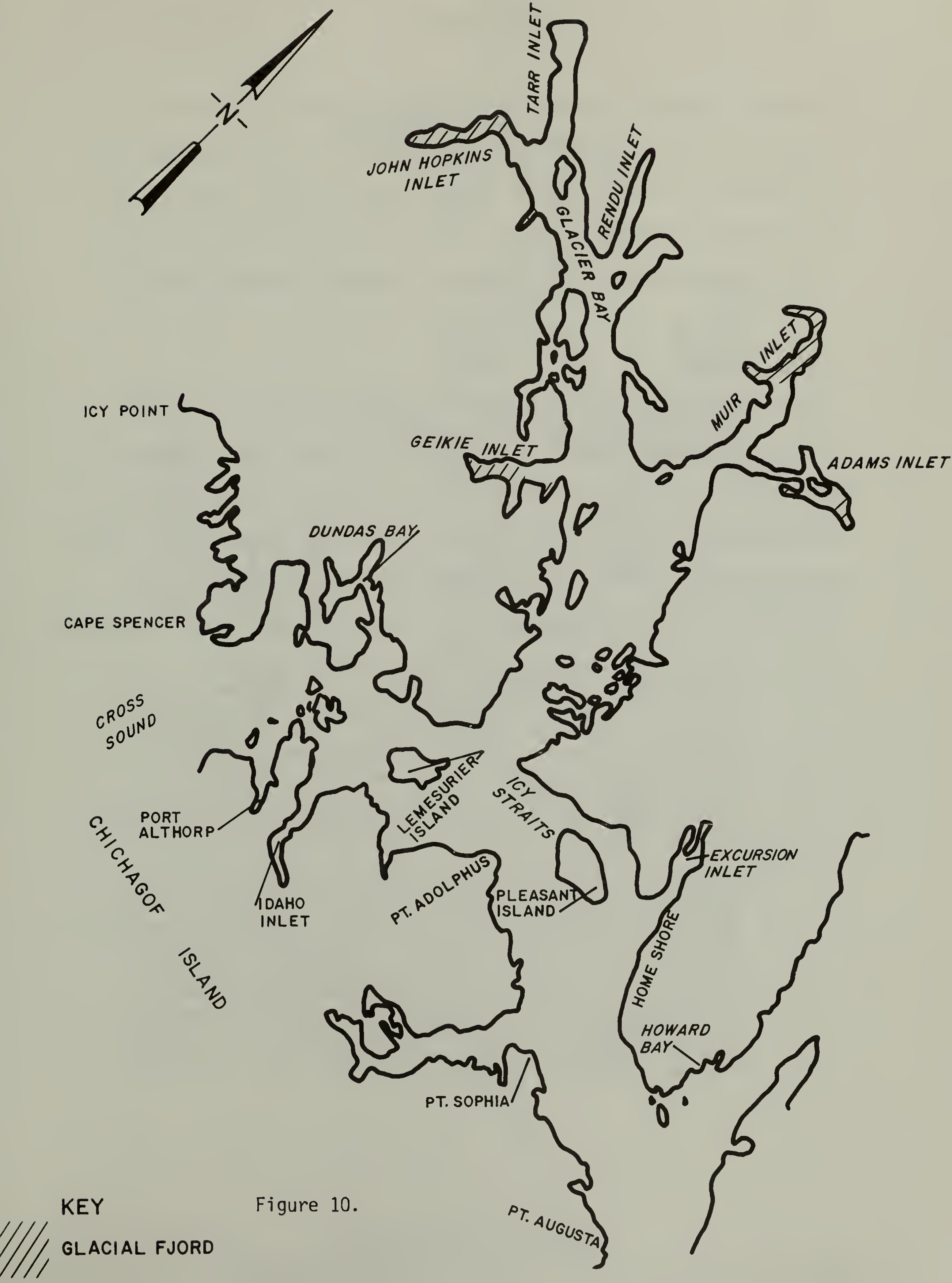


Figure 10.

MARINE GEOLOGY

The overall geology and geologic history of Glacier Bay has been well summarized by Streveler and Paige (1971) and will not be repeated here. The subjects of direct concern for this project are the time of Glacier Bay's emergence from the ice, the fjord basin and shoreline configurations, marine sediment distribution and suspended sediment dynamics.

Glacial Retreat

The position of the glacial fronts in Glacier Bay over the last 200 years has been well documented (Fig. 11). The pace of glacial recession within Glacier Bay has been extraordinary, the trunk tidewater glaciers having wasted away about 15 times more rapidly than anywhere else in the world (Lawrence, 1958). The following explanation of the processes involved in tidewater glacial retreat is taken from Matthews (in preparation):

> The process of glacial retreat in tidewater glaciers is not fully understood but recent work on the tidewater glaciers of Alaska from aerial photographs has revealed some of the processes (Post and LaChapelle 1971). In a retreating tidewater glacier, calving of icebergs from the glacier face takes place directly into the waters of the fjord. Melting directly at the glacier face in contact with warm saline water may also occur. These processes are in addition to the usual one of ablation from sunlight and warm air.
>
> A glacier terminus appears to retreat in a series of very rapid steps with comparatively stable conditions obtaining in the intervening periods. The glacier maintains a tenuous stability at points in the channel where there is a constriction such as a sill. Once the ice retreats behind the sill the ice front recedes very rapidly, usually leaving a very deep basin behind the sill. The recession continues until the glacier sole again rests on a sill. It appears that this process occurs when the water depth is too great for the ice to rest on the fjord floor.

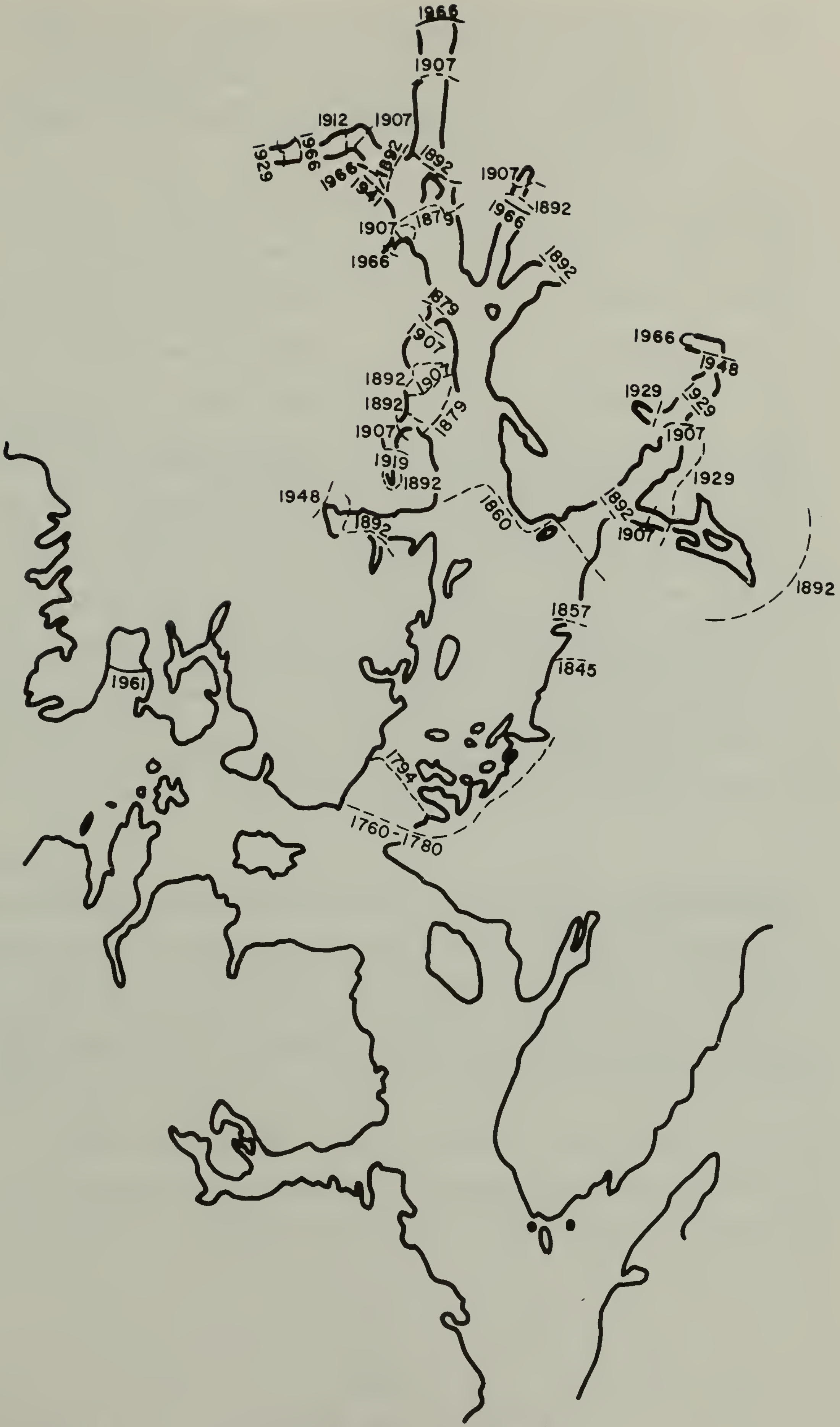


Figure 11. GLACIER BAY, ALASKA
SHOWING FORMER POSITIONS OF TERMINI 1760-1966 (from Bohn, 1967)

> The retreat of the glacier is accompanied by the release of large quantities of ice into the fjord system. The process of restabilization of the glacier at a new sill or headland is often accompanied by an increase in glacial flow due to the adjustment of the steepening of the longitudinal glacier gradient.

The entrance to Glacier Bay has a sill about 22km long with maximum depth of 65m. Evidently, the glacier face was occupying this sill when observed by Vancouver in 1794. By 1860 a major glacial retreat revealed the first deep basin and the major ice terminus rested on the entrance sill of the future Muir Inlet, the shallowest major sill in Glacier Bay. Seventeen years later the glacier had retreated another 37km in the main western arm of Glacier Bay but was still at the entrance sill of Muir Inlet. During the subsequent 30 years (to 1907) there were further retreats; and Muir, Tarr and Johns Hopkins Inlets were uncovered. In the present century, there has been a continued general retreat of the glaciers on the east side of Glacier Bay. In contrast, the glaciers on the west side of Glacier Bay had stabilized by about the mid 1900's and many are now slowly advancing (Streveler, personal communication).

Land Emergence: As the land has been uncovered, it has rebounded. A land emergence rate of 3.96 cm/yr has been estimated for the entrance of Glacier Bay. This is the highest known rebound rate in Southeast Alaska. A maximum vertical emergence of 154cm occurred between 1922 and 1960 (average = 4.05 cm/yr). The average emergence rate for the whole of Glacier Bay is 1.9 cm/yr which, if the rate is constant, would indicate a total emergence of 3.5m from the beginning of the deglaciation of the bay about 170 years ago (Matthews, in preparation).

Other Effects: The results of retreating glaciation on the Glacier Bay marine ecosystem are complex - the distribution and abundance of icebergs change, basin configurations change, freshwater inflow from glacial melt increases and alters circulation patterns which in turn affect a host of biological processes; new substrate becomes available for colonization by benthic organisms; and sedimentation patterns and water transparency change.

The Shoreline

The present Glacier Bay shoreline is marked by a discontinuity between the lower Bay and its more northern tributary inlets. The lower Bay, from the mouth to just north of the Beardslee Islands, is carved from an outwash plain laid down during a previous glacial period. Consequently its margin is characterized by gently sloping shores composed of unconsolidated sediment. The inlets of upper Glacier Bay are characterized by steeply sloping shores usually composed of bedrock.

Bathymetry

Bathymetry (bottom topography) exerts a significant influence on water circulation patterns, the nature and rate of sedimentation patterns and consequently, the biologic habitat. Because of Glacier Bay's dynamic environment, the U.S.C.& G.S. chart (Chart 8202) becomes rapidly outdated.

Bedrock Structure, Relief and Sediment Thickness

Neither bedrock structure and relief nor the thickness of sediment overlying the bedrock beneath Glacier Bay is known. At the head of Queen Inlet, the only place where sediment thickness has been measured, more than 30m of sediments were found to overlie the bedrock (Hoskin and Burrell, 1972).

During the fall of 1978, U.S.G.S. will be conducting side scan sonar studies in several parts of Glacier Bay in an attempt to determine both sediment thickness and the locations of underwater glacial moraines (Bruce Molnia, U.S.G.S., personal communication).

There are three inferred bedrock faults running North-South in Glacier Bay: one through Adams Inlet, one from Tarr Inlet to the mouth of Glacier Bay; and one that splits off this fault, runs to the west then continues south of Willoughby Island and across the entrance of Geikie Inlet. Glacier Bay is included in a high seismic risk zone by the U.S. Army Corps of Engineers (AEIDC, 1976).

Surface Sediments

Surface sediment composition, which largely determines benthic community structure and productivity, is primarily determined by sediment availability and water currents. Glacier Bay is almost entirely blanketed by clayey silts and silty clays (Fig. 12), usually pale to dark grey. These sediments, termed periglacial marine sediments, are typical of the

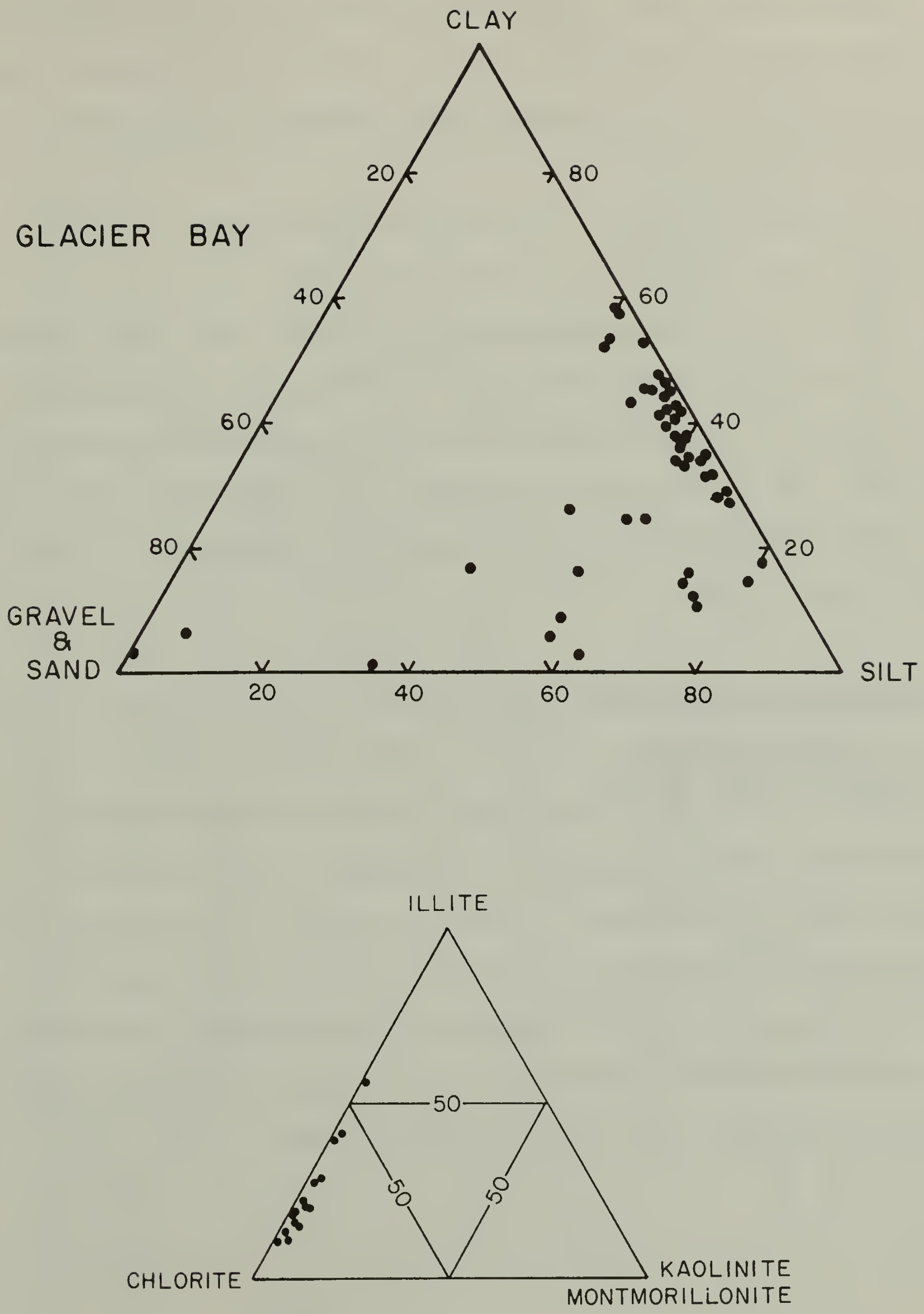


Figure 12: Glacier Bay surface sediment (a) size and (b) composition. (Source: G.D. Sharma (In preparation), Alaska Shelf Hydrographic, Sedimentary and Geochemical Environments.)

southern Alaskan coast. Despite the abundance of calving icebergs in many of Glacier Bay's inlets, erratic, ice-rafted, coarse debris seems to be extremely rare on the Bay's bottom (Wright and Sharma 1969).

The sediment distribution of Queen Inlet has been studied in greater detail than the rest of Glacier Bay. This inlet is characterized by two inlet-long, steep-sided depressions called inlet-floor valleys features not previously recorded from fjords (Fig. 13), which are believed to be evidence for sediment transporting bottom currents (Hoskin and Burrell, 1972). The coarser sandy-silt sediment found on the inlet valley floors contrasts markedly with the mud found on the predominantly flat floor of the inlet (Fig. 14).

The mineralogy of the clay-sized material is simple and uniform throughout Glacier Bay (Burrell and O'Brien, 1970; O'Brien and Burrell, 1970; Burrell, 1971). The sediments are a distinctive subarctic weathering assemblage composed primarily of trioctahedral mica and chlorite (Fig. 12), with minor quantities of plagioclase feldspar, quartz and calcite. These sediments characteristically have high ion exchange capacities. The sediments within Johns Hopkins Inlet are enriched in mica relative to other Glacier Bay sediments, this is probably a reflection of their different source rock (O'Brien and Burrell, 1970).

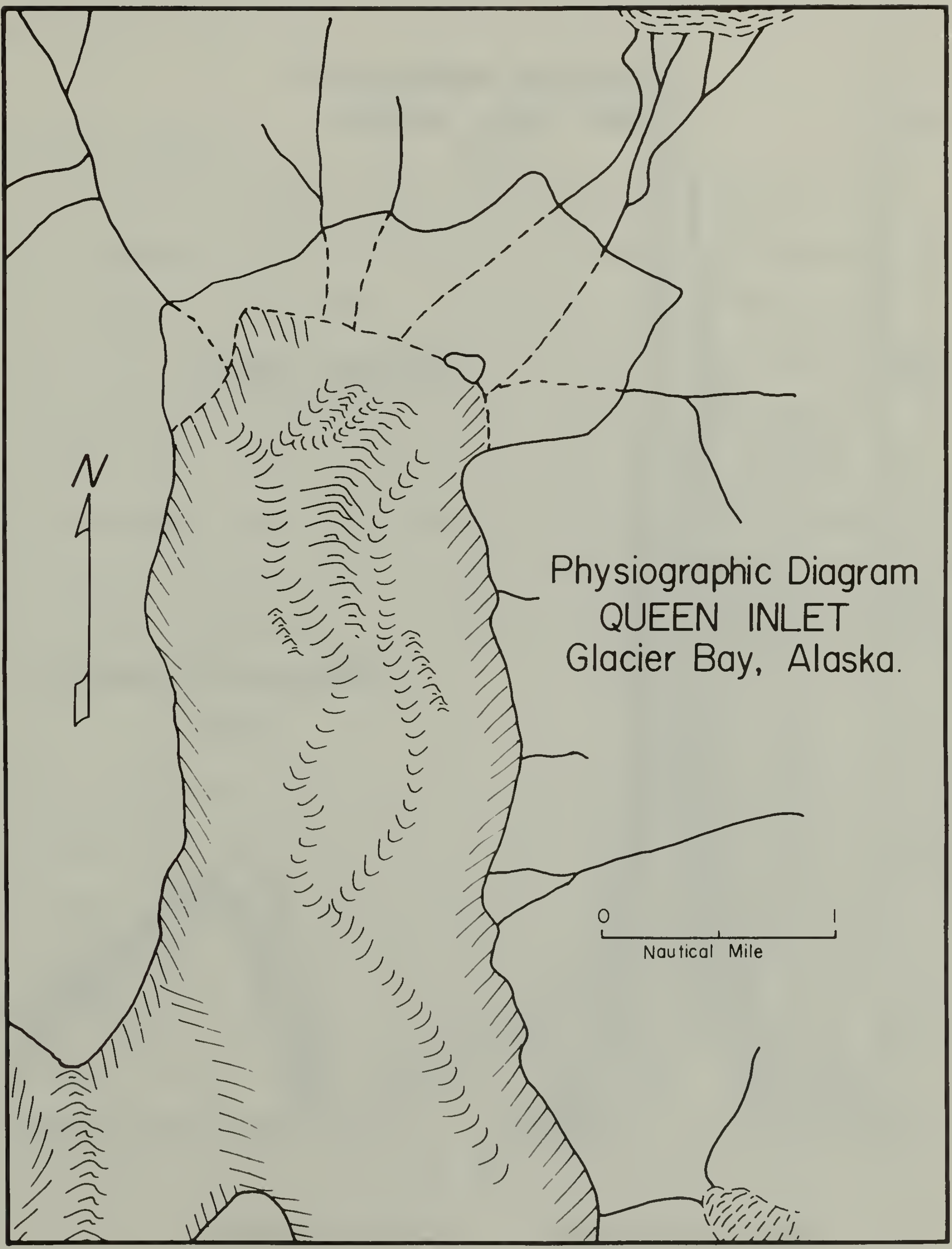


Figure 13. Physiographic representation of Queen Inlet showing the Inlet floor valleys. (reproduced from Burrell, 1973)

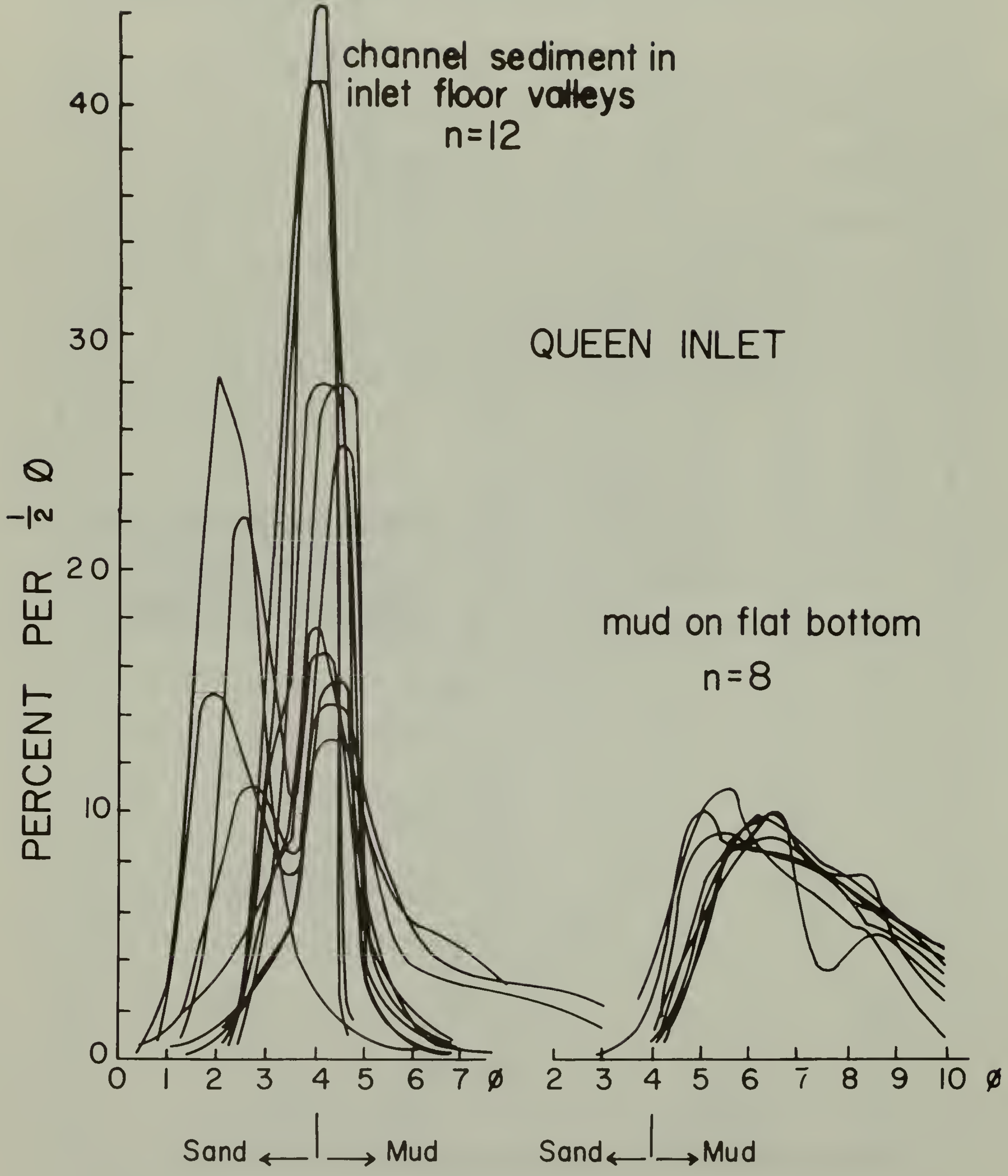


Figure 14. Size-frequency distribution for sediment from the inlet floor valleys and for flat bottom samples in Queen Inlet. (reproduced from Hoskin and Burrell, 1972)

Sediments in upper Glacier Bay (Muir and Queen Inlets) have extremely low particulate organic carbon content (Burrell and O'Brien, 1970); in lower Glacier Bay, values are probably somewhat higher, but have not been measured.

Suspended Sediments

Particles in suspension have significant effects on the physical (e.g. water transparency and light and sound scattering) and biological (e.g. primary productivity and feeding by suspension feeders) properties of seawater. The distribution and composition of suspended matter varies with such factors as fjord type, season, biological production and prevailing water circulation patterns. In Glacier Bay, the dominant form of suspended matter is undoubtedly sediments. Sediment input to Glacier Bay is strongly pulsed seasonally and is primarily dependent on glacial melt. Consequently most sediment is introduced to Glacier Bay through the upper tributary inlets.

The amount or mechanism of transport of sediments over the sills of the upper inlets into lower Glacier Bay is not known. Wright (1971) suggests that turbid suspension coupled with pronounced water column stratification may play an important role in transporting sediments over large areas. The distribution of ice-rafted sediment is determined by iceberg distribution and most large sediment bearing icebergs do not now get outside the upper inlets.

Turbid Outwash Fjords: Large quantities of sediments are introduced to these fjords by glacial meltwater streams that traverse an outwash plain before entering the inlet. The sedimentation patterns in Queen Inlet, a turbid-outwash fjord with a half mile outwash plain (mudflat) between the glacier and inlet has been well studied by Burrell, Hoskin and their co-workers for over 5 years (Burrell and Hoskin, 1970; Burrell, 1971; Hoskin and Burrell, 1972; Hoskin et al., 1976). The following is abstracted primarily from Hoskin and Burrell (1972) and Hoskins et al. (1976).

By far the largest source of suspended sediment to Queen Inlet is the meltwater streams from Caroll Glacier. In early June, meltwater is confined to several major courses over the mudflat. These streams have suspended sediment loads of about 1025 mg/l. By late August to September, glacial meltwater covers large areas of the mudflat and suspended sediment loads average 5810 mg/l. Thus the surface freshwater prism that develops in Queen Inlet during the summer/fall is, in fact a distinctive sediment plume at the fjord head. At low water, the plume maintains its identity for several miles down-inlet. The suspended-sediment load is always in excess of 1000 mg/l at the mudflat-marine boundary; however, once the sediment enters the marine environment, flocculation of particles rapidly occurs along a distinctive front. After flocculation the suspended sediment begins to settle and is present in the water column in discrete layers, probably corresponding to tidal cycles (Fig. 15). In general, sediment loads decrease with depth but increase again near the bottom, perhaps due to resuspension by currents.

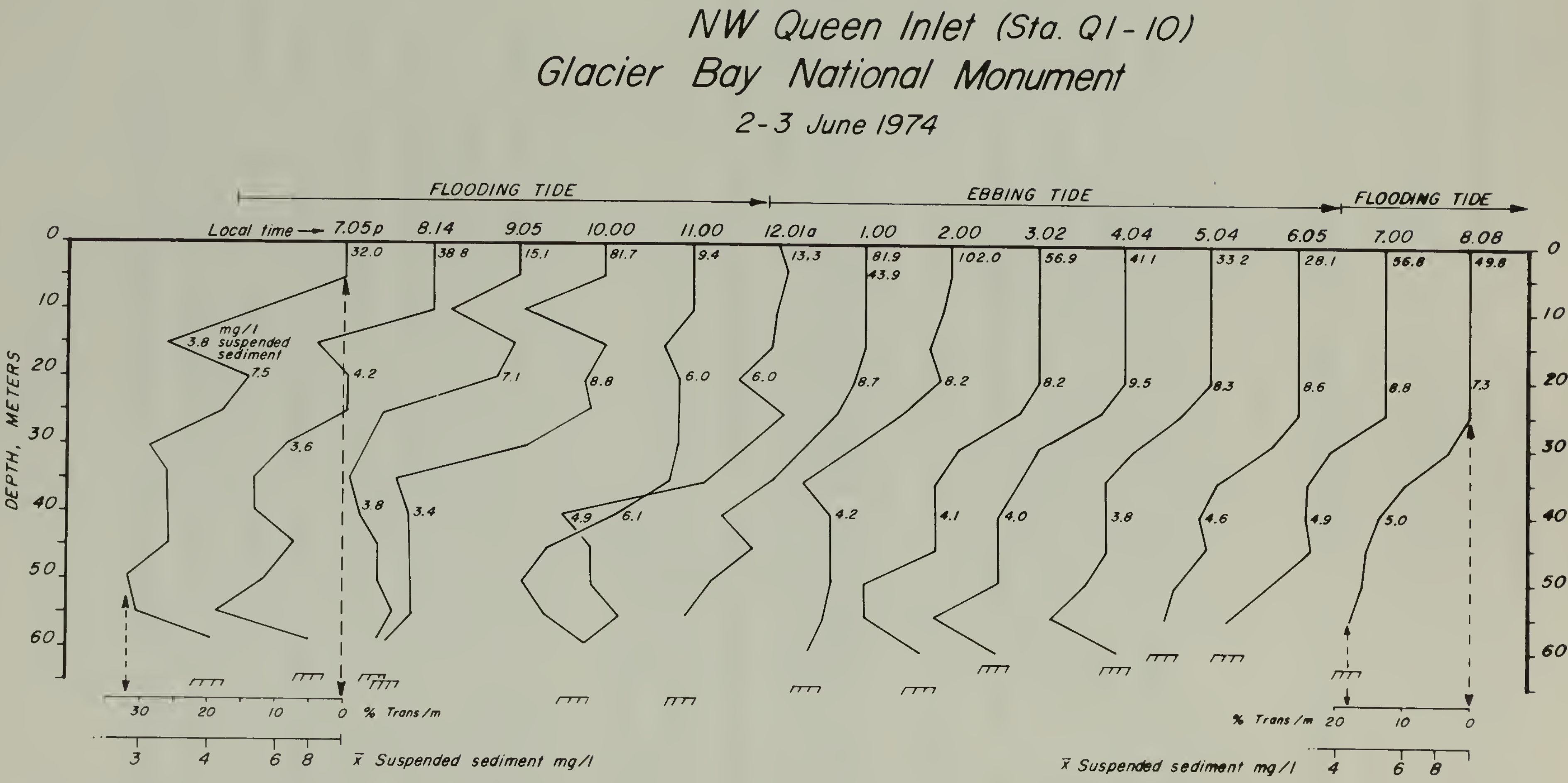


Figure 15. Thirteen hour time series of optical transmission profiles at a single anchor station near the mouth of the main melt water stream at the northwest head of Queen Inlet. (reproduced from Hoskins et. al., 1976)

Settling rates change over the season in response to changes in the amount of freshwater input and type of circulation pattern. In July sediments settle quickly with net settling rates of 5.0 m/hr. In September the sediments stay in suspension longer, settling at a rate of about 1 m/hr.

Sedimentation rates within Queen Inlet are greater than 1 m/yr at the fjord head (rates of up to 2.4 m/yr in the northern corner) and decrease to about .4 m/yr at the fjord's mouth. These calculations are supported by annual marker layers in cores and sediment trap material (Hoskin et al., 1976).

The organic content of the incoming sediments to Queen Inlet is small. Only about 0.08% of the particulate matter entering Queen Inlet is particulate organic carbon. Dissolved organic carbon levels are also very low (0.11-0.14 mgC/l), probably due to a lack of vegetation in the runoff area (Loder, 1971).

Glacial Fjords: Sedimentation processes in fjords with tidewater glaciers and icebergs have not been as thoroughly studied as in turbid outwash fjords. There are two major routes of sediment supply in this inlet type: (1) ice-rafting and (2) suspended particles and bed-load in glacial meltwater streams. Ice-rafted sediments would be expected to show up on the inlet floor as gravel. Bottom sediments collected in Yakutat Bay which, like the glacial fjords in Glacier Bay, receives sediment-laden icebergs did not show the expected evidence for ice-rafting. The coarse particles released from icebergs probably fall into the fluid-like layer of mud at the water-sediment interface and thus escape detection by surface samplers (Hoskin and Mueller, 1977).

The importance of ice rafting in Glacier Bay's iceberg inlets has not been fully assessed but Hoskin and Mueller (1977) suggest it is the main mechanism for introducing particles into upper Muir Inlet. Sediment trap measurements from traps suspended under sediment-laden icebergs in Johns Hopkins Inlet and Mid-Glacier Bay gave 3-250 mg dry sediment /cm /hr (n=6) whereas sediment traps suspended beneath icebergs visually judged to be sediment free gave 0.2-0.3 mg dry sediment /cm /hr. Sediment investigations at the faces of tidewater glaciers in Glacier Bay now underway by Ross Powell of the Institute of Polar Studies, Ohio State University, should go far towards elucidating the sedimentary environment of glacial fjords.

WATER MASS CHARACTERISTICS

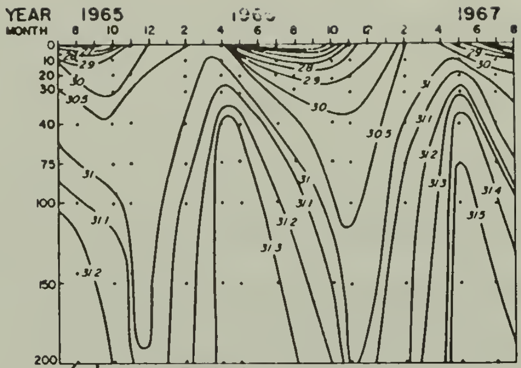
Marine waters are not homogeneous liquids but are characterized by specific temperature, salinity, nutrient and dissolved oxygen profiles. By measuring these rather standard but ecologically important variables, oceanographers can identify discrete water masses and determine water mixing and circulation patterns. These oceanographic variables have been measured at one time or another throughout nearly all of Glacier Bay (See data appendix), primarily by the R/V Acona, the University of Alaska's research vessel. However, only Muir Inlet (Quinlan, 1970; Matthews and Quinlan, 1975), lower Glacier Bay (Matthews, in preparation) and Queen Inlet (Hoskin and Burrell, 1972) have been sampled with sufficient frequency over annual cycles to develop adequate characterizations of their physical oceanography.

Glacier Bay, like other Alaskan fjords, is characterized by two distinct sets of oceanographic conditions over an annual cycle: 1) a winter-spring homogeneous condition which begins to develop in November and is most pronounced in February; and 2) a summer-fall heterogeneous condition where fresh or brackish water overlies a warmer, more saline layer. This latter condition is well developed by June and remains through September. The homogeneous winter condition largely results from the inflow of cold saline water over the sill from December to February and the lack of significant freshwater input. These cycles are clearly illustrated by annual graphs for temperature, salinity, density and dissolved oxygen included in the data appendices.

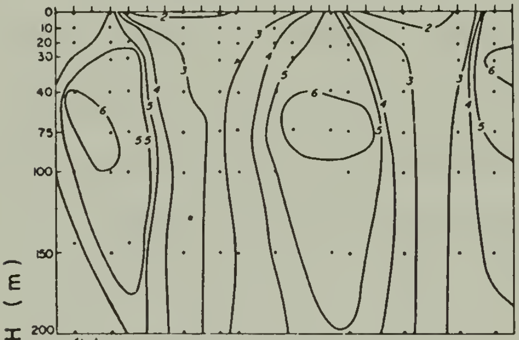
Changes in water density in Muir Inlet as explained in Matthews and Quinlan (1975) illustrate these conditions. Water density, a function of temperature (cold water is more dense than warm water) and salinity (saltwater is more dense than fresh water) is used to identify water masses and to assess their stability or stratification and probable circulation. In Glacier Bay, density structure is affected more by salinity than by temperature variation. Water of about the same density ($_t$=24.5) fills the Inlet from November or December to March or April (Fig. 16). From April to November density decreases at all depths and a large discontinuity (pycnocline) develops in the upper 50 m. Stratification is most pronounced in the fall. Throughout the year surface water density decreases towards the glacier face. This is a result of the glacier melting year round below the water line.

Water Circulation

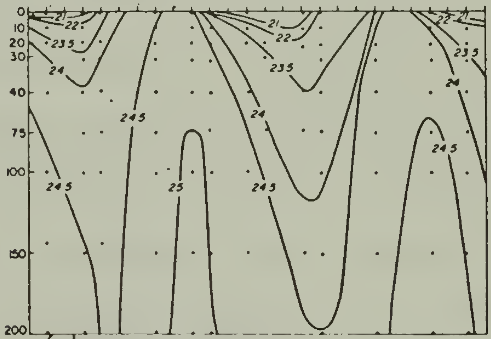
Currents are the major transport mechanism in the marine environment. They influence physical properties (e.g. temperature, salinity, sediments), chemical properties (e.g., nutrients, dissolved oxygen) and biological components (e.g. plankton). Two major kinds of currents - tidal and non-tidal - interact to produce observed water circulation patterns. Total freshwater inflow and tides are the major energy sources that drive currents within Glacier Bay. Winds are probably not important factors in summer circulation. However, the Icy Strait-Cross Sound area is noted for strong winter winds which could seasonally induce significant mixing of surface waters and affect surface transport and circulation (Wing, personal communication). This effect however has not been documented.



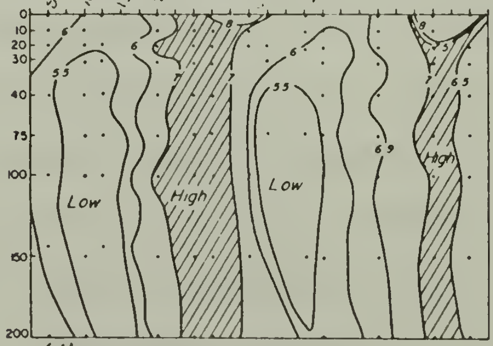
(a) SALINITY (‰)



(b) TEMPERATURE (C)



(c) DENSITY ANOMALY (σ_t)



(d) DISSOLVED OXYGEN (ml/l)

Figure 16: Mean seasonal profiles of salinity (0/00), temperature (C), dissolved oxygen content (ml/liter) and density anomaly (t) in Muir Inlet for the 2 year period July 1965 - August 1967. (reproduced from Matthews and Quinlan, 1975)

The general circulation pattern of fjords has been well summarized by Burrell and Matthews (1974).

> Unrestricted exchange of water between a fjord and its seaward connection can be expected to occur to sill depth only. In the general case the salinity of the surface waters increases from the head to the mouth, while the deeper waters remain uniform. Denser water enters the fjords beneath the outward flowing surface water. Mixing of salt between these two waters occurs predominantly upwards with minimal downward mixing of the freshwater. Rosenberg (1966) has noted that such an entrainment of salt water from below may inflate the original volume of outward flowing surface water by an order of magnitude or more. The extent to which the above generalized circulation pattern is developed depends upon many factors but principally on sill depth, the seasonal volume distribution of freshwater runoff, and the density distribution of the marine water outside the fjordal basin (p. 5).

In a general sense the circulation patterns for Glacier Bay as a unit and of each tributary inlet fjord are similar and follow the preceding description. The variations in detail that do occur arise from variations in sill depth, basin bathymetry, freshwater inflow, available source water and the presence or absence of tidewater glaciers.

Tides and Tidal Currents

Glacier Bay's tidal regime is classified as mixed semi-diurnal. This means that there are two high and low tides of different amplitudes each day. The mean annual tidal ranges at Bartlett Cove and in Muir Inlet are 5 m and 4.25 m respectively.

Tidal currents are strong in Glacier Bay and surface rips are often obvious to observers, especially near Willoughby Island. Over the entrance sill mean and maximum tidal currents are 80 cm/sec and 140 cm/sec respectively, while tidal currents over the Muir Inlet sill average 14 cm/sec with a maximum of about 31 cm/sec. As the glaciers within a tributary inlet retreat, resulting in an increase in the volume of the inlet, the tidal current velocities also increase (Matthews, in preparation).

Bathymetry

The bathymetry (bottom) topography of a fjord basin, particularly its sill depth, have a profound effect on its water circulation patterns. A cross-section of Glacier Bay, showing the depths of its sills (Fig. 17) illustrates the barriers which sills present to the free exchange of water between the fjord basin and outside waters.

Deep Water Renewal

The water present outside the sill of a fjord is termed its source water, meaning that it is potentially available to go over the sill and be retained within the fjord basin. For example, the source water for the Glacier Bay marine system as a whole is Icy Strait water; the source water for Muir Inlet is lower Glacier Bay water; and the source water for Wachusett Inlet is Muir Inlet water.

Source water will only be transported over the sill and trapped in the fjord basin if it is more dense than the water already in the basin at sill depth. Matthews (in preparation) has examined water movement over the Glacier Bay sill and found that deep water renewal takes place every year (between December and April or May) but its completeness depends on

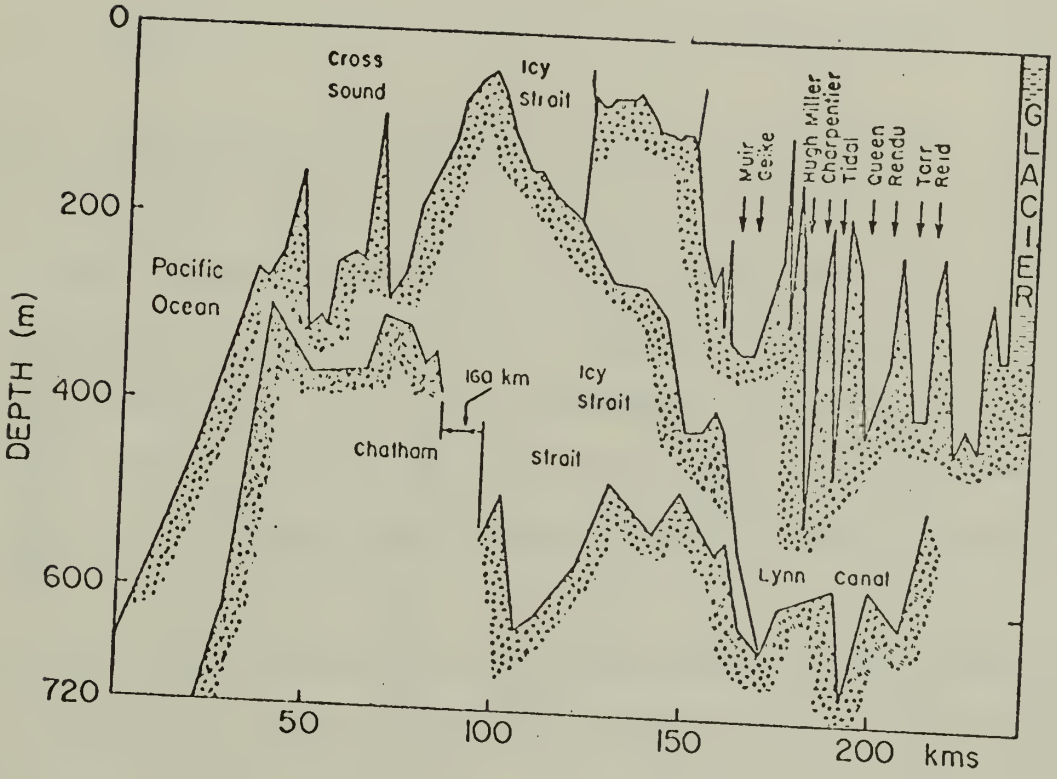


Figure 17. A cross section of Glacier Bay, Cross Sound, Icy Strait and the Inside Passage showing sill depths. (reproduced from Matthews, in preparation)

the intensity of spring thawing and rainfall (freshwater input) and the density of water in Icy Strait to sill depth.

Source water is probably brought over Glacier Bay's broad (22km) sill by tidal action; however, only during the few days near spring tides are tidal excursions long enough to expect significant trapping within Glacier Bay.

Matthews suggests that the bulk of Glacier Bay's source water is derived from water that has traveled about 311 km up Chatham Strait, as the 40m sill in Cross Sound effectively limits the direct access of North Pacific Ocean water to Icy Strait. This suggestion is supported by driftcard data and bouy measurements which show a net transport up Chatham Strait and out Icy Strait driven by the general North Pacific wind induced circulation (Wing, personal communication).

Deep water exchanges between lower Glacier Bay and the upper tributary inlets follow a similar pattern to the one described above; however, exchanges may occur more frequently. Deep water exhange has been shown to occur regularly in Muir Inlet from November to July (Matthews and Quinlan 1975; Quinlan 1970).

Freshwater Input

Freshwater runoff into Glacier Bay is strongly seasonal with significant inputs only occurring from April through November. Matthews (in preparation) has roughly calculated freshwater input to Glacier Bay which

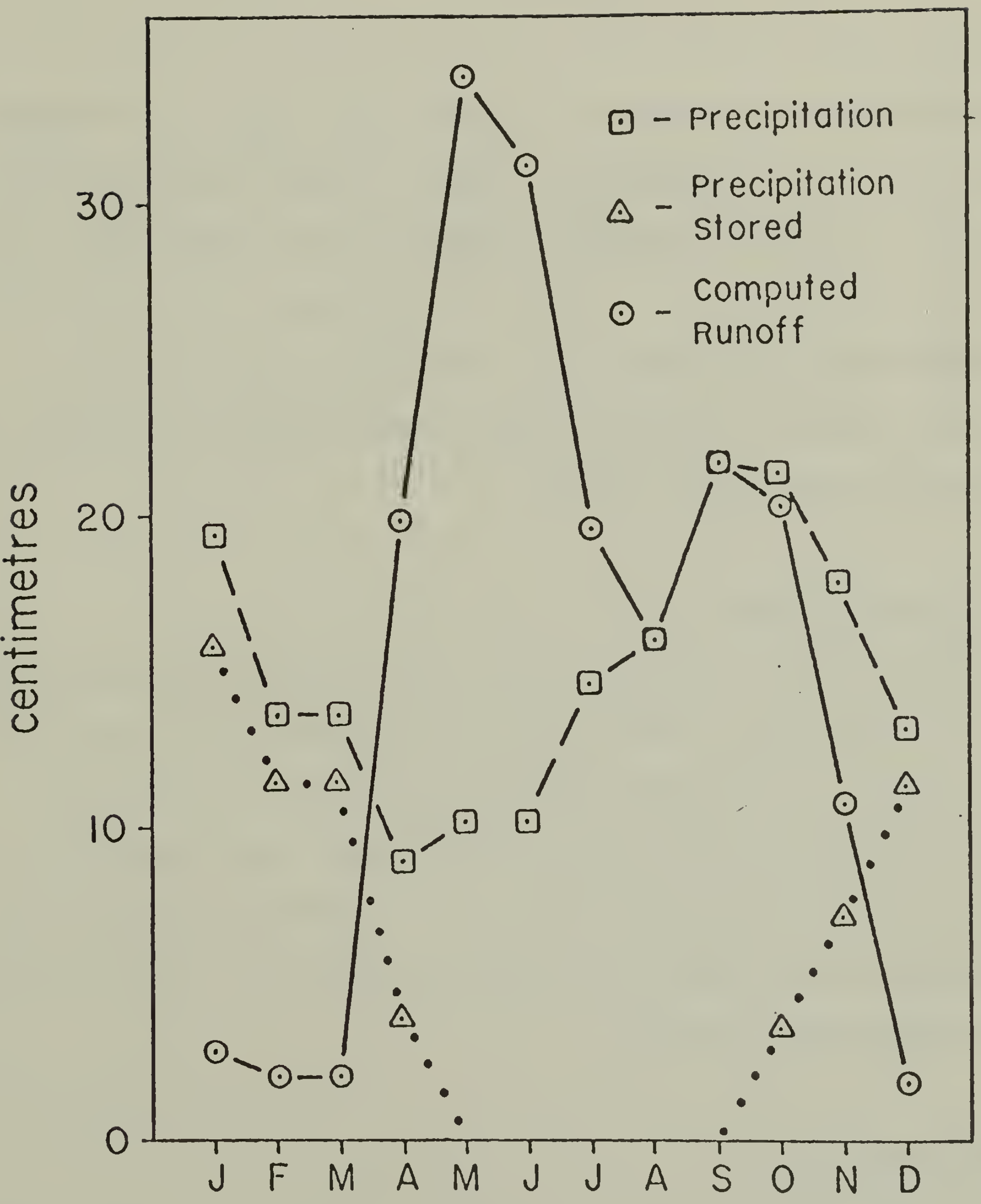


Figure 18. Estimated freshwater input to Glacier Bay. (reproduced from Matthews, in preparation)

takes into account winter storage (Fig. 18). The resultant run off curve peaks in May (due to ice melt) and has a second, somewhat lower peak in September, caused by heavy precipitation.

Glacial Fjords

Within iceberg fjords there is freshwater input year round. Matthews and Quinlan (1975) suggest that tidewater glaciers contribute to the seasonal circulation process by an entrainment mechanism caused by the upward mixing of meltwater from deep-thrust glacial ice. This process explains the distinctively lower temperatures and smaller salinity, density anomaly and deepwater oxygen ranges that occur in iceberg inlets compared with non-iceberg inlets.

Turbid Outwash Fjords

Freshwater inputs to Queen Inlet from Carrol Glacier have been studied by Hoskin and Burrell (1972). They conclude that surface-layer water circulation is more strongly influenced by tidal mixing and marine entrainment during the early part of the summer season, becoming progressively river dominated in the fall. In September the Queen Inlet pycnocline is restricted to the surface 10-15m while in July it extends to a depth greater than 30m.

Water Transparency

Water transparency determines the depth of the euphotic zone and consequently has a large influence on primary production. In Glacier Bay, water transparency is largely a function of suspended sediment in the water column. Observations by C. Jurasz (personal communication) suggest that lower Glacier Bay has become considerably less turbid over the last two or three years. Scattered secchi disc readings are presently the only available data on water transparency in Glacier Bay (see data appendix). More complete secchi disc readings have been made throughout Glacier Bay during June, July, and August for five years by Susan Jurasz (Juneau, Alaska), however, these data have not yet been compiled.

Inorganic Nutrients

Seawater contains only minute amounts of certain inorganic nutrients which are essential for marine phytoplankton and macrophyte growth. The presence of trace amounts of nitrogen, phosphorous and silica in seawater, (micronutrients), as compared with the relatively large proportion of other essential plant nutrients such as ionic potassium, magnesium, sodium, and sulfate, is indicative that the micronutrients may become limiting. The circulation of these critical biologically active nutrients, as well as their distribution in the water column, depends both on biological and physical processes.

With the exception of one annual sampling program at Bartlett Cove (Chang, 1971; see data appendix), inorganic nutrients have been sampled only irregularly in Glacier Bay (see data appendix). To draw conclusions from this scanty data would be unwise. Rather the data are interesting for the questions they suggest about annual plankton and nutrient cycles in Glacier Bay.

Annual sampling programs of inorganic nutrients have been undertaken in two other Southeast Alaskan fjords; Valdez Arm (Goering et al., 1973) and Endicott Arm (Wallen and Hood 1968). Both these fjords show generally similar annual patterns and in a gross sense Glacier Bay probably follows this description. Maximum concentrations of inorganic nutrients occur throughout the water column during the winter when there is a homogeneous water column and minimal phytoplankton production. Marked reductions to near depletion of these nutrients occur in the waters above the pycnocline during the spring because of intense phytoplankton blooms. Nutrients remain at a low, though sometimes fluctuating level throughout the summer. During the late fall as the pycnocline breaks down, higher winter nutrient values are re-established through deep water renewal and mixing. Deep water nutrient concentrations remain at a relatively stable level throughout the year.

The major source of nutrients to Glacier Bay is probably the marine waters entering from Icy Strait. Loder (1971) found the inorganic nutrient content of glacial meltwater to be low compared to marine source water. Milner (1978) reported concentrations less than 1ppm for nitrate and orthoposphate in two Berg Bay streams, Nunatak Creek, Wolf Creek and the Burroughs River stream.

Nitrogen: Nitrogen is often thought to be the nutrient most limiting to phytoplankton growth in the marine environment. Nitrate (NO_3), the most abundant oxidized form of nitrogen usually available to marine plants (Goering et al., 1974), varies from complete depletion in Glacier Bay's surface waters in May or June (the time of the major spring bloom) to over 10ug-at/l in the winter (see data appendix). The precipitous drop in nitrate at Bartlett Cove coincides with the sharp peak of phytoplankton abundance (Chang 1971). The distribution and relative importance of ammonia, the preferred nitrogen source of most marine phytoplankton, is not known for Glacier Bay. In Port Valdez, high ammonia concentrations are correlated with peaks in zooplankton abundance and periods of low nitrate concentration (Goering et al., 1973).

Phosphorus: Inorganic phosphate (PO_4) which exists in seawater in many forms is the primary source of nutrient phosphorus for the phytoplankton. In Valdez Arm, PO_4 is in intermittent short supply during intense blooms and may have become the major limiting nutrient (Goering et al., 1973). The few data available on phosphorus for Glacier Bay show it following a seasonal distribution similar to nitrate (see data appendix). Summer values in the euphotic zone (waters with enough light to support plant growth) above the pycnocline ranged from .07ug-at/l to 1.0ug-at/l. During winter, phosphate values are more uniform throughout the water column and are about 2ug-at/l.

Silica: Dissolved silica, which is required by diatoms to build their frustules, exists exclusively as $Si(OH)_4$ in most marine waters. Glaciers are a rich source of silica, making the coastal waters of southeast Alaska contain unusually high concentrations of this essential nutrient. Silicate concentrations of 60ug-at/l have been reported in Glacier Bay (Sharma, 1970). Seasonal cycles of $Si(OH)_4$ in Glacier Bay's surface waters generally follow the patterns of nitrate and phosphate, however silica does not appear to become depleted enough to ever be limiting (see data appendix).

Spatial Variations: Although the data are insufficient to document differences in nutrient distribution throughout Glacier Bay, a comparison of data taken in July of 1967 in upper and lower Glacier Bay and in Icy Strait suggest some interesting differences (Fig. 19).

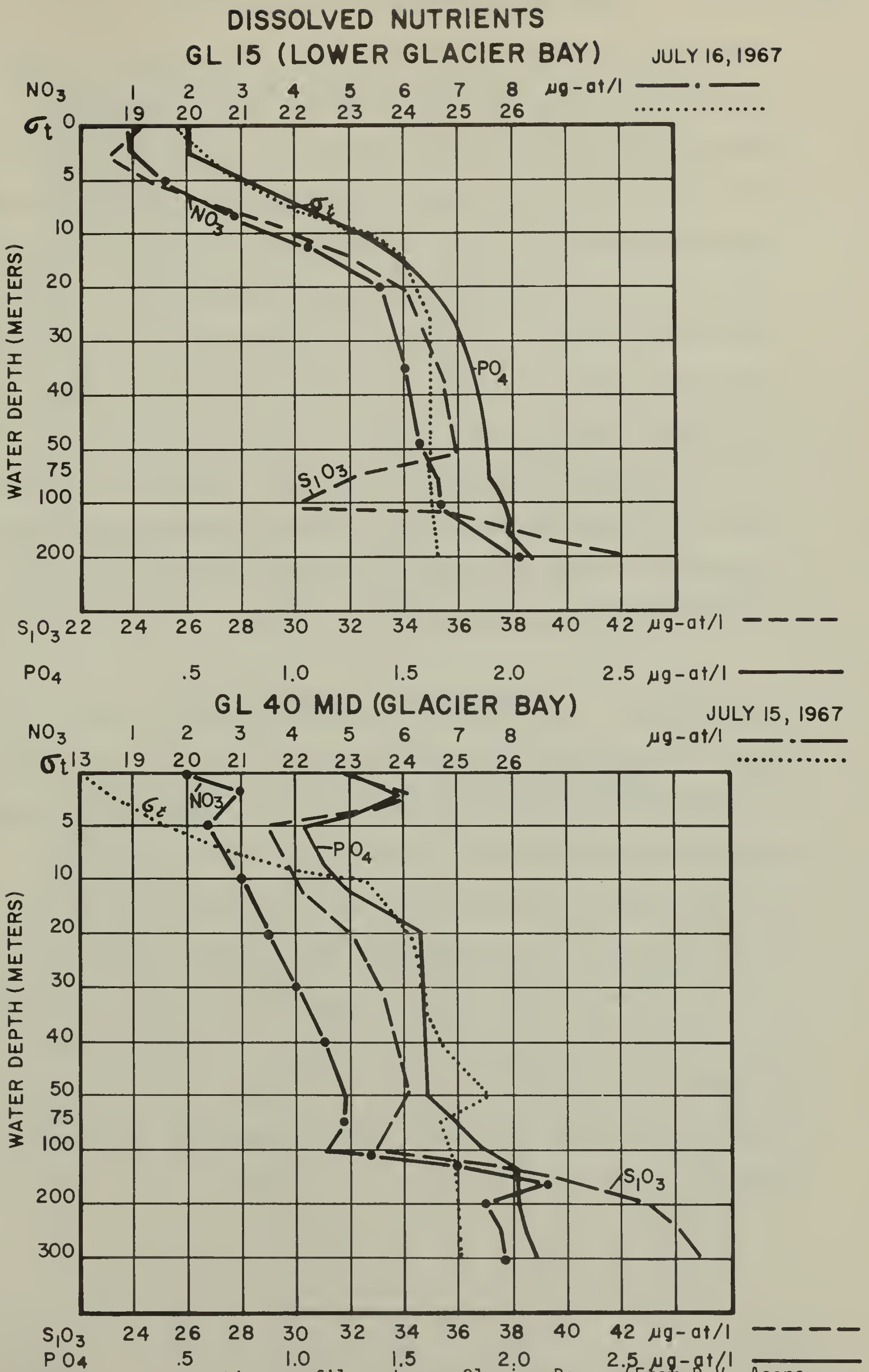
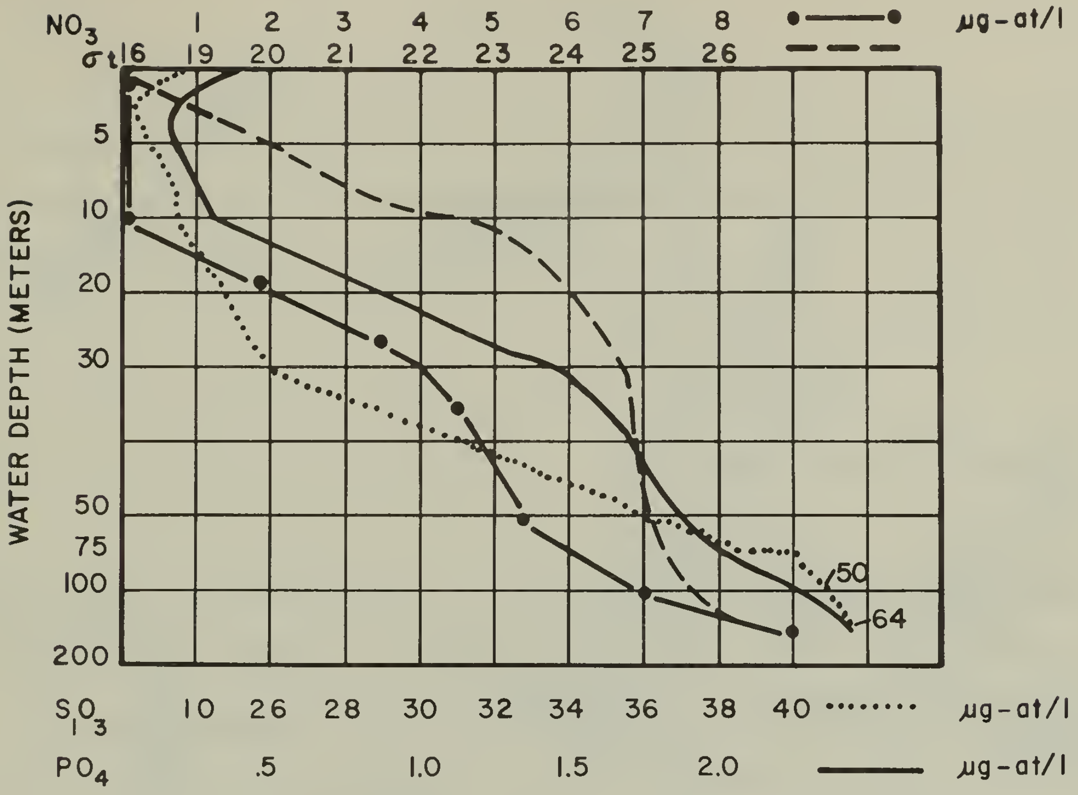


Figure 19. Nutrient concentration profiles, Lower Glacier Bay. (From R.V. Acona data archives; Institute of Marine Science, University of Alaska, Fairbanks.)

A pycnocline is present at all three stations, although it is least developed in the lower bay. In Icy Strait, nitrate is completely depleted from the top 10 m of the water column and phosphate and silicate are also very low. This nutrient situation is typical of an area with a phytoplankton bloom. In lower Glacier Bay, nutrients are somewhat depleted from the top 5 m but are at levels which would still support phytoplankton growth. Nutrient values at Station GL 40 in the upper Bay are abnormally high for summer values. The possibility of light limitation on plankton productivity is suggested. Nutrient depletion of the waters at GL 40 is much more pronounced in May, when the pycnocline is already formed but sediment input is still relatively low (Fig. 20). Light and freshwater limitation of summer phytoplankton productivity has been reported for Valdez Arm (Goering et al., 1973).

Glacial fjords: The influence of tidewater glaciers on water nutrient content and production has been the subject of some published (Dunbar, 1954) and much unpublished speculation. Although there are few nutrient measurements in Glacier Bay's iceberg inlets, measurements made in Greenland fjords by Apollonio (1973) are of some interest. He found an iceberg inlet to have significantly higher nitrate and silicate concentrations than an adjacent control fjord without tidewater glaciers. It is doubtful that the ice is a significant source of additional nutrients. A more likely explanation is that the circulation pattern close to the glacier front brings deep water nutrients closer to the surface.

ICY 20 (OFF PLEASANT ISLAND) JULY 16, 1967



GL 40 (MID GLACIER BAY) MAY 15, 1967

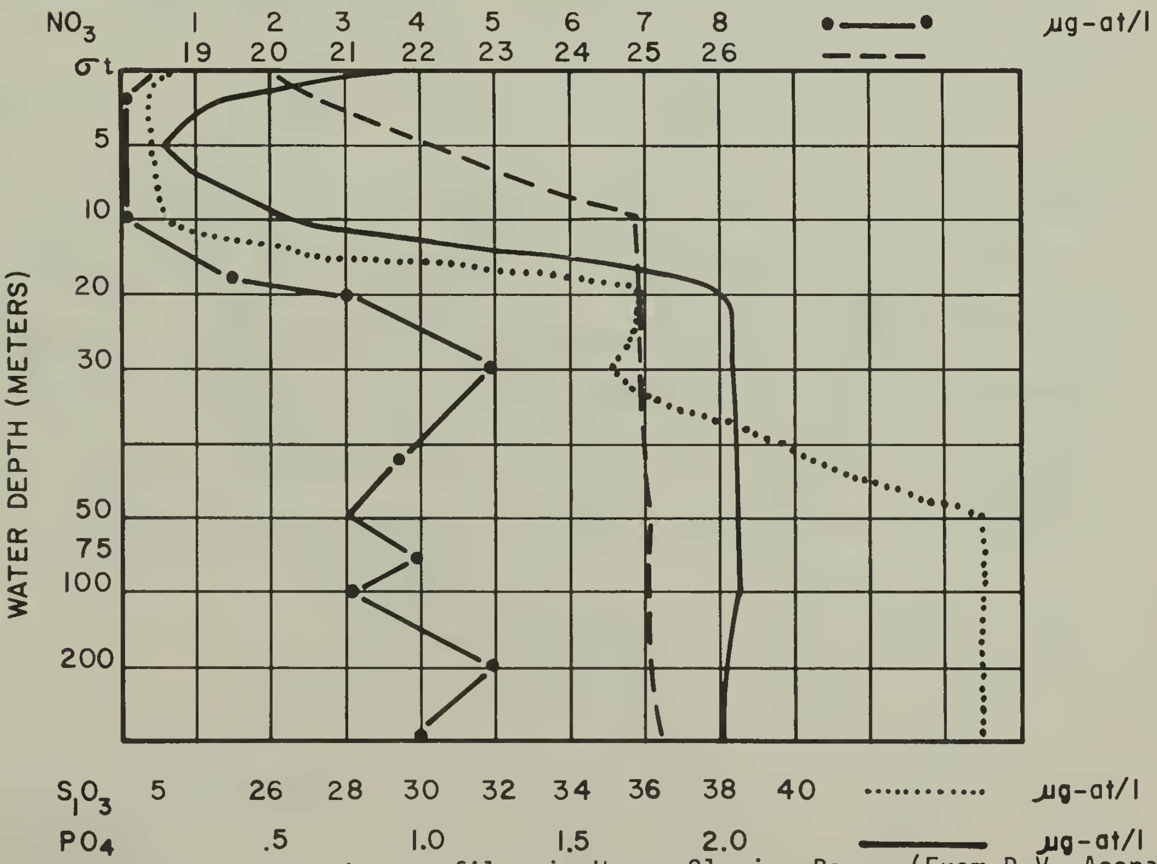


Figure 20. Nutrient concentration profiles in Upper Glacier Bay. (From R.V. Acona data archives, Institute of Marine Science, University of Alaska, Fairbanks.)

HABITAT TYPES

Glacier Bay is a large, heterogeneous system which contains a multiplicity of habitat types. Before describing each ecosystem component, an overview of some major habitat divisions as illustrated in Figure 21 will be discussed.

Upper/Lower Glacier Bay

Lower Glacier Bay: Lower Glacier Bay is characterized by a wide shallow entrance sill, a deep, flat basin, and gently sloping, well vegetated shores. Freshwater input is from several large streams as well as surface waters from the upper tributary inlets. The lower Bay's biological assemblages, particularly the pelagic components, are well developed and large numbers of migratory animals such as whales, phallaropes and pelagic fish are seasonally abundant. Most commercial and sports fishing occurs in the lower Bay.

Upper Glacier Bay: Upper Glacier Bay is divided into two major arms into which flow smaller tributary inlets. These more recently deglaciated tributary fjords are characterized by narrow sills, and steeply plunging shores with only modest amounts of vegetation. The pelagic components of the upper Bay inlets are poorly developed, and with the exception of seals, they have smaller seasonal population influxes.

GLACIER BAY HABITAT TYPES

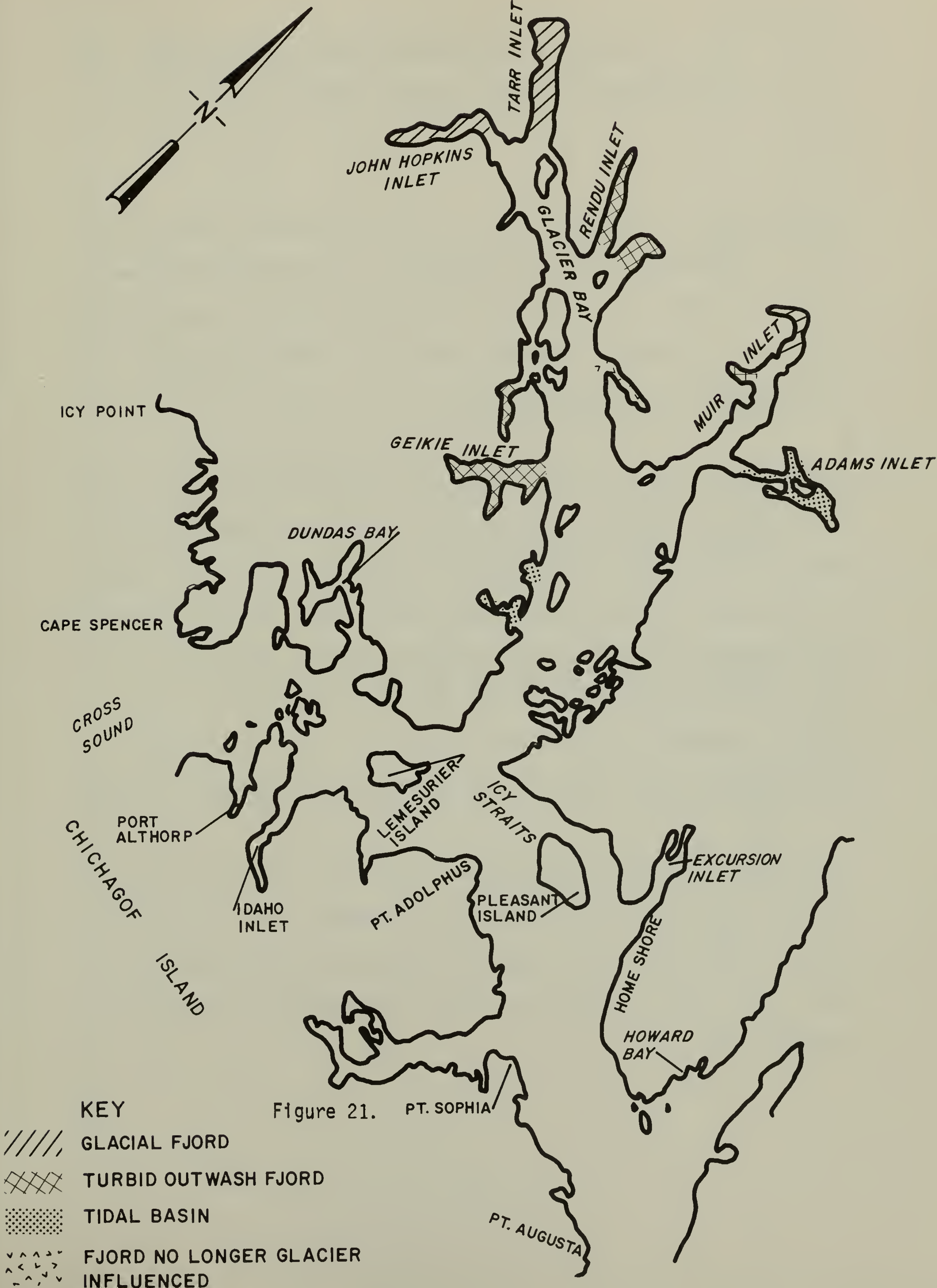


Figure 21.

Inlet Type

Glacier Bay has 15 tributary inlets, ten of which are also fjords. The physical characteristics of these tributary inlets are summarized in Table 2.

Glacial Fjords: A glacial fjord is a narrow steep-sided coastal inlet fed by a tidewater glacier at its upper end. The presence of tidewater glaciers within a fjord is known to influence water body characteristics and circulation patterns (Matthews and Quinlan, 1975) and possibly system productivity (Apollonio, 1973).

Turbid Outwash Fjords: Fjords where glaciers terminate on land and send their meltwater into the tidewater via a freshwater stream system are termed turbid outwash fjords (Burrell and Matthews, 1974). In contrast to the somewhat clearer water of the glacial fjords, large quantities of glacially ground sediment from the deposits between the glacier and fjord are transported into the inlets by glacial meltwater. The discharge, transportation and ultimate disposal of these large sediment loads must represent a great stress in the local biological environment.

Fjords no longer glacier-influenced: Tidal Inlet is the only example of this fjord type that is characterized by relatively clear inflowing water and a freshwater input schedule determined solely by precipitation. Such fjords are common in British Columbia and are described by Pickard (1967).

Table 2 - Physical Characteristics of selected tributary fjords of Glacier Bay

Inlet Name	Length (km)	Mean Width (km)	Surface Area (km^2)	Max. Depth (m)	Sill Depth (mouth- head) (m)	basins
Muir Inlet	33.9	3.5	104.93	318	62	1
Adams Inlet	19.1	1.9	10.34	73		1
Wachusett Inlet	4.8	1.1	4.82	84		1
Tidal Inlet	8.7	1.3	8.67	228	54	1
Queen Inlet	12.4	2.4	27.92	109	94	1
Rendu Inlet	17.2	1.7	26.71	182	128	1
Tarr Inlet	17.8	3.3	51.0	384	384	1
John Hopkins Inlet	16.7	2.4	34.17	448	219	1
Reid Inlet	3.9	10.5	5.77	42	42	1
Hugh Miller Inlet	17	2.2	37.53	98	21,42	2
Charpentier Inlet	10.7	1.3	9.39	157	140	1
Geike Inlet	14.8	2.2	34.17		69,201,204	3

(source; G.D. Sharma (in preparation), Alaska Shelf Hydrographic, Sedimentary and Geochemical Environment)

Non-fjord basins: These estuarine environments tend to have more gently sloping shores, clearer waters and greater species diversity than the fjord tributary inlets.

Intertidal Zone

With a greater than 650km shoreline and an approximately 4.5m tidal range, Glacier Bay has an extensive intertidal zone. As the tide alternately covers and exposes this area, the organisms living there are subjected to a host of physical (e.g. heating, desication), chemical (e.g. oxygen availability) and biological (e.g. marine or terrestrial predators) changes. Only a hardy well-adapted assemblage of organisms can withstand the many stresses of the intertidal environment.

The set of organisms found in any particular intertidal area depends on many factors but principally on the duration of exposure to air, the substrate type, the degree of exposure to wave action, wind and sun, and in the case of Glacier Bay, probably the turbidity of the water and the time since deglaciation.

Glacier Bay's intertidal zone can be roughly separated into the low relief, gently sloping shores of the lower Bay, primarily composed of unconsolidated sediments and the more northern part of the Bay where steep rocky cliffs come down to the water's edge.

A preliminary survey of several intertidal habitats in Glacier Bay was carried out by Mueller (1973). A map of his sampling stations and a checklist of the organisms he found is included in the data appendix. From this survey and from general observations on other Southeast Alaska intertidal environments, Mueller suggests that Glacier Bay's intertidal communities are roughly similar to those of other inland passage shores. Consequently, the survey work done by Wing (1978) in several Southeast Alaskan inlets and by Calvin (1977) in Berners Bay provide interesting comparative work for serious students of Glacier Bay's intertidal community.

Rocky Shores: The species composition and dynamics of the rocky intertidal community found in Torch Bay along the Monument's exposed outer coast has been well studied (Duggins and Quinn 1977; Quinn and Duggins 1977; Duggins, unpublished); much less work has been done on the more protected rock shores within Glacier Bay. Because of the major differences in water characteristics and exposure between the two areas, the biotic communities are probably considerably different. Wing (1978) has reported certain species differences between intertidal areas along the outer coast and inside passage.

Vertical zonation (the tendency of a particular species to be found only within a restricted range of tidal heights) is the most obvious feature of Glacier Bay's rocky intertidal assemblages. For a brief discussion of zonation and an introduction to the rocky intertidal organisms found at Bartlett Cove, see Duggins (unpublished).

Up Bay, species diversity drops. A dense barnacle/rockweed/mussel zone, however, continues on suitable substrates close to the heads of the inlets and glacier faces, except on surfaces deglaciated in the last couple of decades or scoured by floating ice.

Where data are available, Duggins (personal communication) distinguishes three zones in the rocky intertidal of Torch Bay. The upper zone is characterized by barnacles (*Balanus* spp., *Chthamalus dalli*) and periwinkles (*Littorina* spp.); the middle zone is dominated by rockweed (*Fucus distichus*), and mussels (*Mytilus edulis*) along with their associated infauna; the lowest zone is distinguished by the presence of large brown algae (kelp), particularly *Alaria* spp.

Rocky intertidal zone assemblages provide important food resources for a wide variety of birds, notably gulls, sea ducks and such shorebirds such as oystercatchers and sandpipers. Other animals, both marine (e.g. fish, crabs) and terrestrial (e.g. coyotes, wolves, bears, and weasels) come to the rocky intertidal during different tidal stages to feed.

Shores Composed of Unconsolidated Sediments: A variety of unconsolidated substrate types including cobble, sand, mud and mixed sediments are found throughout Glacier Bay, but especially in its lower reaches. Little work has been done to characterize these communities, but studies carried out in Prince William Sound (Hubbard, 1971; Feder *et al*. 1973, 1976) and in Three Saints Bay Kodiak Island (Nybakken, 1969) would serve as useful starting points for comparative studies. Reconnaissance surveys have been made in scattered locations throughout Glacier Bay by Mueller (1973) and Kendziorek (unpublished), and the Bartlett Cove clam population has been briefly examined by Gallucci (1978).

Intertidal sand and mud flats are important feeding areas for gulls and the hundreds of thousands of migrating shorebirds that pass through Glacier Bay.

High Intertidal Meadows: Fringing meadows are found along the shores of some of the Beardslee Islands, the Bartlett River and in scattered estuarine locations in other parts of lower and middle Glacier Bay. The meadows around Goose Cove, Muir Inlet are the northernmost extent of this habitat in the Bay. Although this habitat has not been studied in detail in Glacier Bay, Streveler (personal communication) describes the plant community as being dominated by the sedge Carex lyngebyei at the water's edge and rye grass (Puccinetta nutkaensis) in the supralittoral zone. These meadows provide important habitat for nesting and molting waterfowl and probably contribute locally significant quantities of organic material to the detrital food chain.

SECTION II

A SUMMARY OF INFORMATION ON THE BIOLOGICAL ENVIRONMENT OF GLACIER BAY

PRIMARY PRODUCERS

Plants, through the process of photosynthesis, use the sun's energy to build organic material. The amount of organic matter produced per unit time by a system's plants is called its primary production and sets a theoretical ceiling for the biomass of consumers (animals) that can be supported. Primary producers within the Glacier Bay marine ecosystem include the phytoplankton, macroalgae or seaweed, benthic microalgae and small stands of intertidal and subtidal herbaceous plants. The relative importance of these primary producers is not known in Glacier Bay. In most marine systems, phytoplankton account for the largest proportion of the system's primary production, and this is probably true in most areas of Glacier Bay. However, in nearshore areas, particularly where there are suitable shallow subtidal substrates, kelp may provide a greater amount of production than plankton (Duggins, personal communication). Identifying the importance of the various primary producers in Glacier Bay will require further research.

Primary Producer Model

A model of primary production for Glacier Bay is shown in Figure 22. In this and all subsequent models, the diagrammatic representation of components in the models is similar and follows the conventions of Forrester (1968, 1971). Appendix III contains a brief discussion of the conventions and symbols used in the model diagrams.

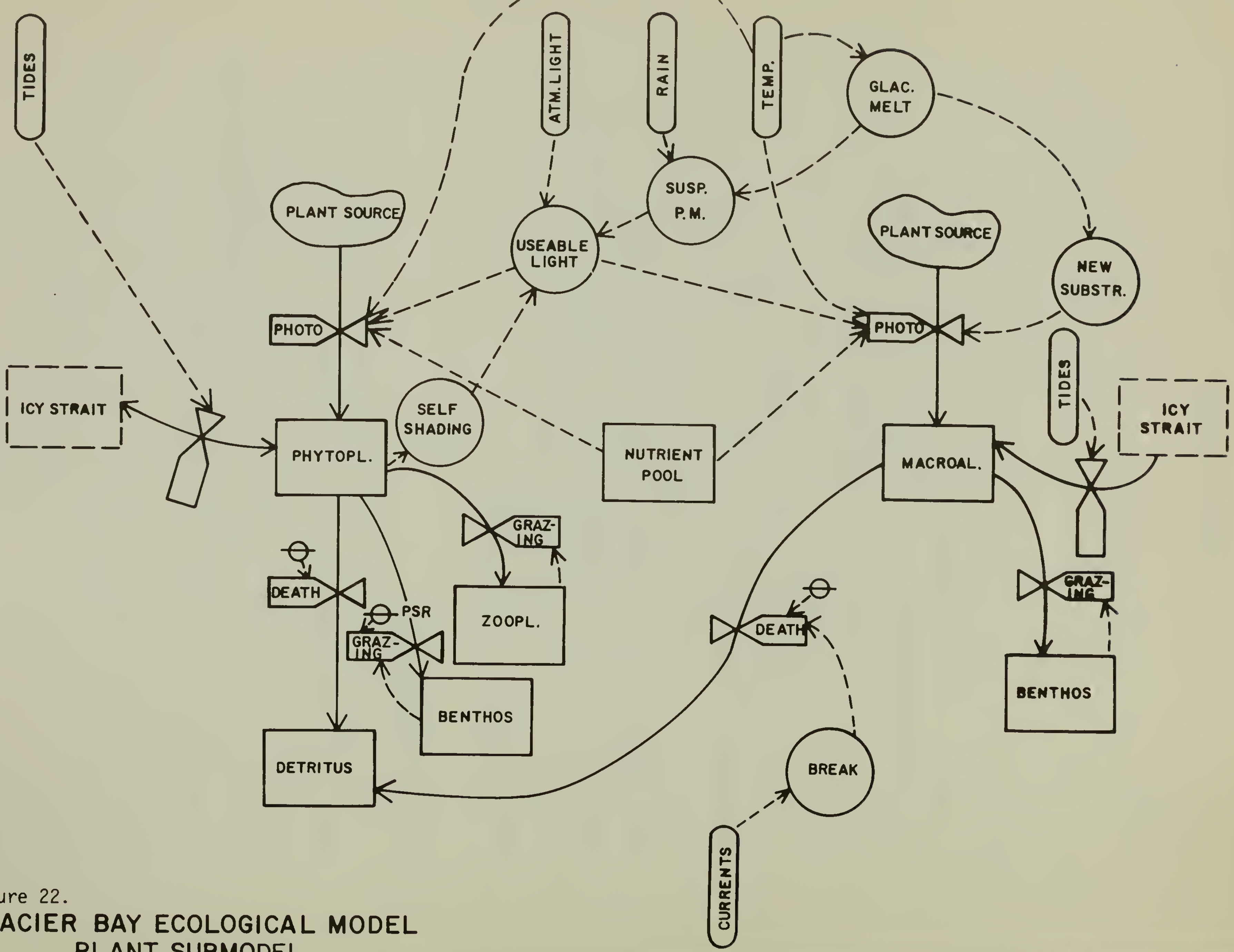


Figure 22.
GLACIER BAY ECOLOGICAL MODEL
PLANT SUBMODEL

The two major categories of primary production, phytoplankton and macroalgae are shown separately. The major source for both of these groups is that which grows in the Bay. The sources as shown in the model cannot really be measured, and are only of ancillary interest to the concepts displayed. Phytosynthetic development of new material is, in both cases, dependent upon nutrient availability, water temperature and useable light, which is limited in turn by suspended particulate matter. Phytoplankton plants, can as they develop, shade themselves thus decreasing the photosynthesis of all plants. For macroalgae, the existence of a suitable substrate is an additional factor regulating growth.

In addition to within system production, significant quantities of phytoplankton and unattached macroalgae may be brought in from Icy Strait with the tide as shown in the model. Other sources of organic material to the system include detritus brought in over the sill during bottom water renewal, and, in the lower Bay, small amounts of land produced organic material brought in by streams. A discussion of the major characteristics of each of the primary producer categories follows.

Phytoplankton

Phytoplankton are free-floating, either unicellular or colonial, marine plants. They are the major producers of organic material in most marine environments and form the ultimate food base for the ocean's living resources.

The productivity, species composition, and distribution of phytoplankton in Glacier Bay is almost entirely unknown. The only data available are from one station in Bartlett Cove over a one year period (Aug. 1968 - Aug. 1969; Chang 1971), where sampling frequency was not adequate to insure that all blooms or the peak of the major bloom was recorded. However, data from this study (see data appendix) suggest the phytoplankton cell numbers in Bartlett Cove remain low from August to mid-March. In March, April and May, cell numbers increase reaching a sharp peak of about 1,000,000 cells/liter in June. It is not known whether the sample year is typical, but these data suggest that the phytoplankton population numbers are slightly lower and the bloom considerably later than either of the blooms that typically occur in Auke Bay (Bruce 1969) or Port Valdez (Goering et al., 1973).

Species Composition: The annual occurrence of the more common genera of phytoplankton collected in Bartlett Cove are listed in Table 3. Diatoms dominate the phytoplankton population throughout the year, although their relative importance somewhat decreases during July and August when dinoflagellates increase in number. The dinoflagellate bloom in Bartlett Cove was, however, less pronounced than in Icy Strait (Chang, 1971), Auke Bay (Bruce 1969) or Port Valdez (Goering et al., 1974).

Species of the diatoms *Chaetoceros* and *Thalassiosira* largely comprised the June bloom. In Auke Bay *Thalassiosira nordenskioldii* usually produces the mid-April bloom (Bruce, 1969).

TABLE 3. SEASONAL OCCURANCE OF COMMON PHYTOPLANKTON GENERA (CELLS/ML) IN BARTLETT COVE, 1968-1969 FROM CHANG (1971).

Diatoms	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Chaetoceros		0.2	2.6	18.4	15.5	150.7	3.2		1.0	0.4		
Detonula		0.1							0.1	0.7		
Leptocylindrus									0.7	0.2		
Navicula			12.4	14.6	4.6	16.0	19.6	5.9	0.2	0.2		
Nitzschia	0.4			4.9	.5	23.0		2.9	0.2	0.1	0.5	
Skeletonema				1.4				2.7		0.5		
Thallassiosira		0.3	13.4	151.3	12.3	479.0	12.6	6.7	2.6	0.9	0.2	0.1
Dinoflagellates			3.5		8.8		32.1	8.1	2.6	0.4	0.1	
Unidentified Genera	0.7	0.4	6.1	2.3	1.6	360.3	25.2	35.3	6.9	7.0	2.5	0.2
Total Cell Number	1.1	1.0	38.0	192.9	43.3	1029	92.7	61.6	14.3	10.4	3.3	0.3

Spatial Patterns of Species Composition: Phytoplankton populations show patchy distribution patterns in response to small scale environmental anomalies and water circulation patterns. Glacier Bay, with its heterogeneity of environments, undoubtedly has variations in plankton distribution and production. In an unpublished study of Lynn Canal and Chatham Strait, Williamson (1974) found fewer phytoplankton species in the highly stratified low salinity waters of upper Lynn Canal than in the more marine, better mixed stations of Chatham Strait. Goering et al. (1973) also report differences in species composition between Port Valdez (a fjord) and Valdez Arm (the adjacent Bay). Differences in species diversity are not correlated to either phytoplankton abundance or production.

Loder (1971) describes a biologically active layer as occurring just beneath the surface freshwater/marine mixing layer. This layer is characterized by almost normal salinity, low particulate matter, high dissolved organic matter and particulate organic carbon and low C/N ratios. Phytoplankton are probably concentrated in this layer. This biologically active layer is absent from the head of Queen Inlet but is probably present near the mouth of Queen Inlet.

Primary Production: Primary production rates have not been measured in Glacier Bay. In Port Valdez annual net primary production averages about 150g/m^2 -yr (range:116gC/m^2 -yr to 213 g C/m^2 -yr) with peak production rates occurring during the spring bloom. This number is somewhat lower than waters in adjacent Valdez Arm (220 g C/m^2 -yr). The major difference in production in these two systems occurred in summer, at which time production in Port Valdez was light-limited because of large influxes of silt-laden fresh water.

Nutrient and hydrographic data for upper Glacier Bay suggest that summer plankton production may also be light limited.

Macroalgae

The contribution of Glacier Bay's macroalgae stands to the system's total annual primary production is not known, and thus, it is difficult to compare it to phytoplankton production. Macroalgae may be more important as a source of detritus to the system, than as a direct food source. Several animals, both marine, and in the winter, terrestrial do however, feed on macroalgae. Seaweeds, especially kelp, provide habitat for discrete assemblages of organisms.

Species Composition: The macroalgae of Glacier Bay of the intertidal zone was briefly surveyed by Mueller (1973; See data appendix). More detailed seaweed surveys have been undertaken in Berners Bay (Smith 1972; Calvin, 1977) and Kachemak Bay (Dames and Moore, 1976) and a less detailed but more extensive survey of many Southeast Alaskan inlets by McRoy et al. (1971). There are no data available on shallow subtidal algae in lower Glacier Bay. As they could be a major contributer to the Bay's productivity, this factor should be investigated.

Spatial Patterns in Species Composition: The lower Bay's intertidal is richer in macroalgae than the upper inlets, probably because of less stressful light and salinity conditions. Tlinget Point generally marks the dividing point between the diverse macroalgae communities of the lower Bay and the rather monotonous *Fucus* dominated stands of the upper Bay. Colonization of newly exposed substrate by macroalgae is probably rapid. In Prince William Sound, bare rocks thrust into the intertidal zone by the great earthquake of 1964 had, by 1968, developed near normal algae communities (Haven, 1971).

Primary Production: Production rates for certain macroalgae species, especially kelps, are among the highest on earth. The times of peak production for macroalgae are somewhat different from phytoplankton. The smaller perennial kelps (*Agarum* sp. and *Laminaria* spp.) grow most rapidly in winter and early spring when the water is clear, the overstory reduced, and nutrients abundant. The larger annual kelps (*Nereocystis inetheana* and *Alaria fistulosa*) reach peak biomass in spring and early summer. By mid to late summer they become senescent and begin to enter the detrital food web.

The biomass of the primary producers is diminished by the grazing of zooplankton and benthic organisms, and for both groups, the primary producers are a major source of food. The grazing rate of benthic organisms is in turn dependent upon the phytoplankton sinking rate (psr). Remaining unconsumed plants on death are added to the detritus compartment.

ZOOPLANKTON

The zooplankton and micronekton include all the smaller (generally less than 10mm) animals found in the water column. While many of these animals are capable of substantial vertical movement, their lateral swimming ability is minimal.

Zooplankton graze on phytoplankton and enriched detritus. These animals provide the first link in the marine food web and are a source of food to higher trophic levels including carniverous zooplankton. Zooplankton also provide an important food source to fish, birds, benthic animals and humpback whales as well as increasing the flow of organic matter to the bottom (because of the relatively fast sinking rate of their fecal pellets) and being important for nutrient regeneration above the pycnocline during the summer months.

Zooplankton include temporary members termed meroplankton (larval stages of benthic animals) and icthyoplankton (fish eggs and larvae), as well as more permanent members such as copepods and euphausids.

The Zooplankton Submodel

The zooplankton submodel shown in Figure 23 illustrates the three divisions of zooplankton small, large, and meroplankton. Since almost nothing is known about Glacier Bay's zooplankton populations, much of the information displayed in the submodel is based on general knowledge.

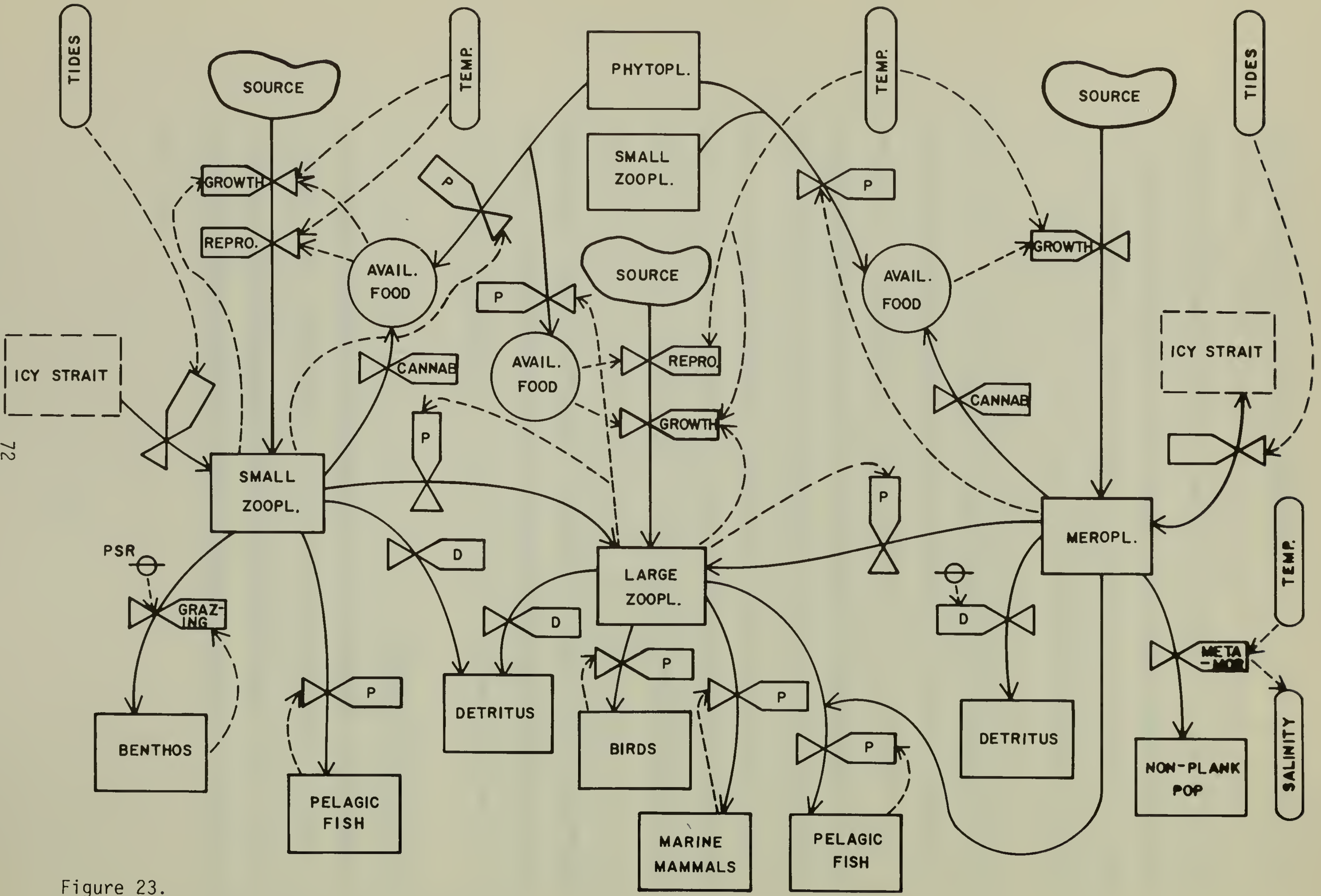


Figure 23.
GLACIER BAY ECOLOGICAL MODEL
ZOOPLANKTON SUBMODEL

The only thorough zooplankton study available for Southeast Alaskan waters was done in Auke Bay (Wing and Reid, 1972). A less detailed study which focuses on icthyoplankton was carried out in Lynn Canal and Chatham Strait (Mattson and Wing, 1978).

Zooplankton biomass seems to be largely determined by the available food supply and temperature, while salinity probably is more important in controlling species composition. Small zooplankton and meroplankton are grazed on by carniverous members of their own species group, (cannibalism), by large zooplankton, and by small pelagic fish. Small zooplankton become available to benthic organisms as they sink. The biomass of small zooplankton and meroplankton in Glacier Bay is also a function of a population being moved in and out by the tide.

Meroplankton metamorphose to adults and leave the plankton, the time and rate of which is a function of temperature and salinity. The large zooplankton consist primarily of euphausids who are largely phytoplankton feeders. During July and August, euphausids are an essential food source to both marine mammals and birds.

Species Composition

Large populations of euphausids (probably of the genus Thysanoessa, C. Jurasz, personal communication) are regularly found at the water's surface in mid and lower Glacier Bay from mid-July through August. Wing (personal communication) suspects that these are juvenile animals. Euphausids migrate vertically in the water column with maximum daytime concentrations probably found at about 150 to 200 meters. The reasons for their being seen closer to the surface are not known. Species lists from two zooplankton samples collected in Glacier Bay in August 1963, by the NMFS Auke Bay Laboratory are provided in the Data Appendix.

Seasonal Patterns: Since no annual zooplankton sampling program has ever been carried out in Glacier Bay, seasonal abundances of zooplankton are not known. Zooplankton abundance typically follows but lags phytoplankton abundance. The small zooplankters probably show more marked seasonal changes in abundance than do the larger forms such as euphausids. Many small copepods have an overwintering egg stage while some of the large forms over-winter as adults, feeding only occasionally. Wing (personal communication) suggests that large zooplankton can survive extended periods of starvation. For example, *Parathemisto libellula* a relatively large planktonic amphipod found in Glacier Bay survived in the laboratory up to 60 days without feeding.

Icthyoplankton (fish eggs and larvae) and larvae of benthic invertebrates are periodically abundant components of the zooplankton. Fish eggs are most abundant in other Southeast Alaskan inland waters in May and fish larvae abundance peaks in May and June (Mattson and Wing, 1978). Jurasz (personal communication) has observed large numbers of crab larvae in Glacier Bay in late May.

Spatial Patterns: Differences in zooplankton species composition undoubtedly exist between the lower and upper portions of Glacier Bay. Wing (personal communication) suspects the major shifts are in the surface forms and not so much in the deep dwelling plankton.

BENTHOS

The benthos represent a relatively stable component of the seasonally pulsed Glacier Bay ecosystem. Benthic animals provide a year round food source for many of the animals that remain in Glacier Bay after the short spring/summer season of high production.

The Benthos Submodel

The benthos (bottom-living animals) are usually divided into subcategories depending on where they live, either in the sediments-infauna; or on the sediments-epifauna. The benthos submodel shown in Figure 24 is based on this division. The relationships shown in both categories of the submodel are similar, and are treated in a similar manner. The "sources" shown are to provide continuity to the model framework and are external to the concepts modelled.

Infauna

Almost nothing is known about Glacier Bay's subtidal benthic communities. With the exception of one set of samples from Queen Inlet (Table 4, Hoskin et al., 1976) no data on subtidal benthic infauna are available.[1] The subtidal benthic infauna described for several tributary fjords of Prince William Sound (Hoskin, 1977; Feder et al., 1973) are probably more similar to the Glacier Bay fauna than the assemblages described for Torch Bay and Dixon Harbor (Mueller et al., 1977), on the Monument's outer coast. These inferences were used in the development of this portion of the submodel.

---

[1] George Mueller, University of Alaska, collected samples from Muir Inlet in 1976. Presently, there are not funds available to allow their processing.

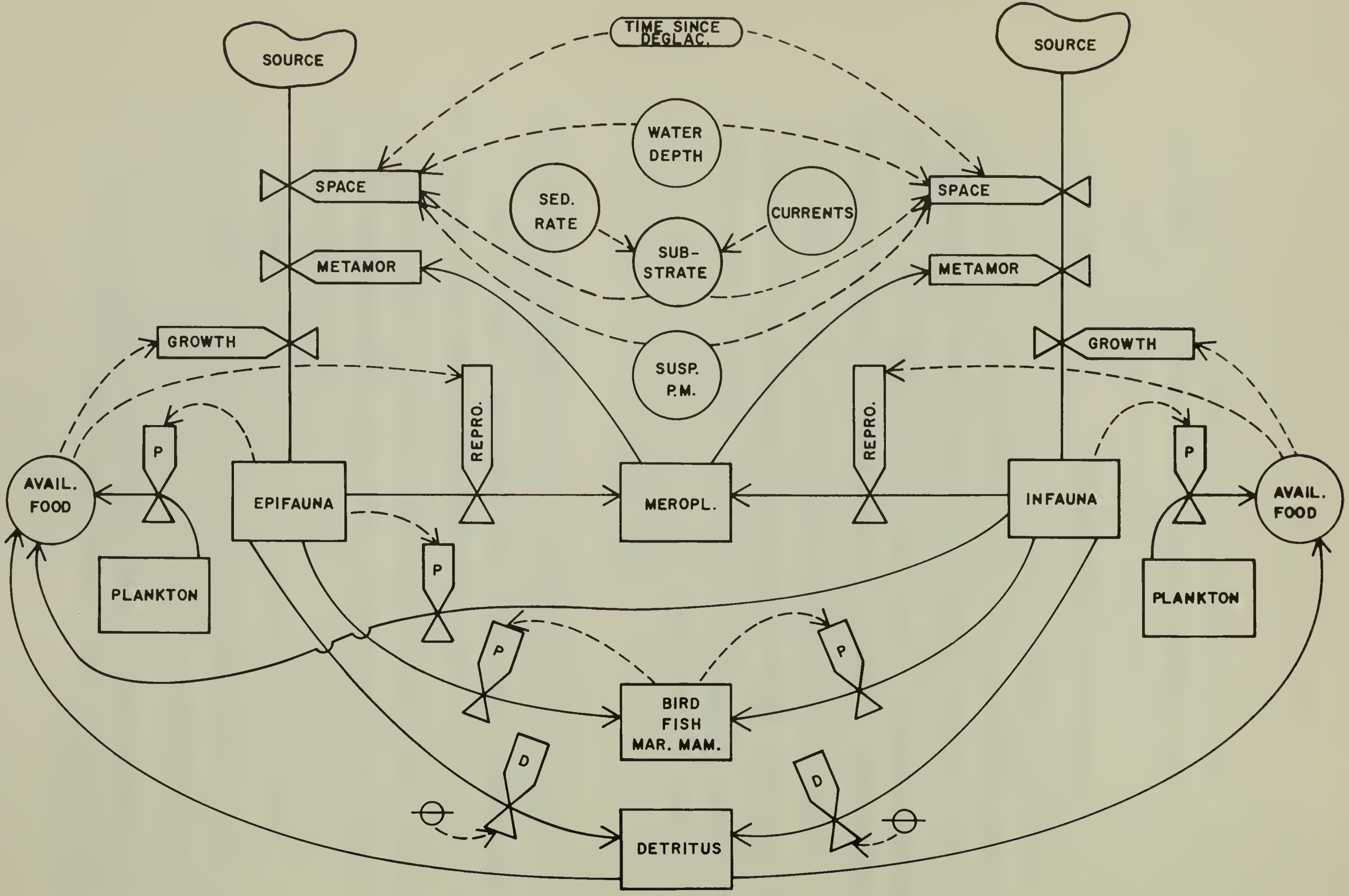


Figure 24.
GLACIER BAY ECOLOGICAL MODEL
BENTHOS SUBMODEL

Table 4. Location of Van Veen Grab Stations and Species Recovered From Sediment Washings, Queen Inlet. 64 l Sediment Washed From Each Station; Grain Size Data Not Available. from Hoskin *et* al. (1976).

		Number	Blotted wet wt., g
N.W. Queen Inlet head, water depth 64m			
brittle star frag., unidentified fragment		1 + 1	.003
Off delta of eastern snow melt-water stream, 2.5 nautical miles (4.6km) from inlet head, water depth 157m			
Crustacea	*Eudorella emarginata*	6	.025
Annelida	*Spiophanes cirrata*	1	.002
Pelecypoda	*Axinopsida serricata*	1	trace
On sill in S.W. inlet mouth, 4.5 nautical miles (8.3km) from inlet head, water depth 115m			
Crustacea	*Eudorella emarginata*	3	.007
Amphineura	*Chactodierma robusta*	1	.178
Annelida	*Amphicteis scaphobranchiata*	4	.045
	Aricidea sp.	1	trace
	Heteromastus filiformis	8	.340
	Lumbrinereis similabris	2	.125
	Meliana cristata	4	.131
	Nepthys cornuta	1	trace
	N. *ferrugenia*	2	.175
	Tharyx sp.	47	.204
	Unidentified copepod, cumacean, and pelecypod	3	.011+
	TOTAL	76	1.216+

Epifauna

The epifauna of Glacier Bay have not been systematically sampled but information from exploratory commerical fish trawls (Anonymous, 1970, U.S.D.O.I., 1967), catch records and numerous observations suggest fairly abundant and ecologically important shrimp and, to a lesser degree, tanner, Dungeness and blue king crab populations. All three of the crab species are fished commerically while no important commercial fisheries presently exist for Glacier Bay shrimp. Juvenile and adult crabs are also an important food resource for high level consumers and are particularly vulnerable when they are molting. They are consumed by demersal fish and marine mammals and, in turn, consume both dead and decaying mollusks and crustaceans and live epifauna and infauna such as shrimp, small crab, barnacles, mussels, and worms.

In Muir Inlet, University of Alaska scuba divers observed a seemingly barren bottom except for fairly large numbers of pink shrimp and juvenile tanner crabs (Fred Short, personal communication). These two species were also the most commonly taken animals in a series of NMFS exploratory fishing drags (Table 5, Anonymous, 1970).

Shrimp are probably the most important food resource for higher level consumers in the upper inlets. They are thought to be important components of the diets of humpback whales, seals, diving ducks, murres, and most demersal fish. The food habits of pandalid shrimp are poorly known, but they are generally thought to be predators and scavengers (Barr, 1970), feeding on dead animal material as well as living organisms such as euphausids, limpets, annelids, and other shrimp. Examination of the guts of several shrimp from Muir Inlet showed them to be filled with mud (Fred Short, personal communication). The above factors are all displayed in the submodel diagram. Other factors such as the possible migration of shrimp and crabs into and out of the bay or the cannibalistic habits of some epifauna are not shown in order not to overly complicate the diagram.

The importance of organic material brought in with deep water over the Glacier Bay sill as a food source for shrimp and other deposit-feeding epifauna is not known but may be important.

Relationship of Benthos to the Physical Environment

The importance of sediment type in determining benthic species assemblages and abundances has been well documented. Within Glacier Bay, the following other gradients of environmental variables are also influencing benthic community development as displayed in the submodel.

1. sedimentation rates: Hoskin and Mueller (1978) suggest that the distribution and abundance of macrobenthos (especially infauna) may be controlled by sediment flux in glacially active fjords. For example, in Queen Inlet the number of species increased from 2 to 13, the number of individuals increased from 20 to 760/m, and the biomass increased from .03 to 12.16 g/m (blotted wet weight) in going from the head of the inlet where sedimentation rates are over 1 m/yr. to the sill crest 7.2km away where sediment flux is greatly reduced (Table 4; Hoskin et al., 1976). Mueller (personal communication) suggests that the pulsed nature

of the sedimentation patterns in Glacier Bay allows colonization of newly deposited sediments during the winter when conditions are more stable.

2. age of sediments: The time since the bottom has emerged from the ice also affects the maturity and diversity of the community. The successional development of benthic communities in subarctic fjords has never been studied.

3. food sources: Detritus probably plays a central role in driving the Glacier Bay benthic subsystem. The sources of detritus to the benthos are several:

1) material derived from within system production;

2) kelp and other material produced elsewhere and washed in on the surface;

3) detritus brought in from Icy Strait through the process of bottom water renewal; and

4) materials produced on land and in the case of salmon, in the ocean and carried into the Bay with freshwater inflow.

Except in certain lower Bay locations, the first two sources are probably of much greater significance than the last.

Distribution of Benthos in Glacier Bay

Based on the information described above, the following hypotheses can be made about Glacier Bay's benthic population. The lower Bay probably supports the most diverse and abundant benthic communities. As one moves up Bay, both benthic diversity and abundance probably decrease with the heads of the turbid outwash fjords having the most depauparate fauna. The importance of shrimp as a food source for other ecosystem components probably increases as one goes up the Bay.

FINFISH

Finfish play an important role in the Glacier Bay marine system - as predators, as prey and as transporters of energy within and outside the system. The Bay's halibut and salmon populations support commercial, subsistence and sport fisheries.

Finfish Submodel

The fish submodel shown in Figure 25 is divided into three major categories, small pelagic, large pelagic and demersal fish. Both groups of pelagic fish include anadromous species that pass through Glacier Bay both as young on their way to sea and as adults returning to freshwater streams to spawn. Other fish species also migrate into and out of Glacier Bay in response to such factors as food availability, salinity, temperature, bottom water renewal, and internal biological urges. For simplicity, only selective mechanisms are shown in the model diagram. The extent and control of most migrations into and out of Glacier Bay are poorly understood.

Fish biomass in Glacier Bay has not been assessed. Populations are controlled by many factors with food availability being one of the most important. Available food comes from several sources: zooplankton, benthic organisms, and other fish. Fish populations are in turn preyed upon by marine mammals, birds, and contribute, upon death, to the detritus compartment.

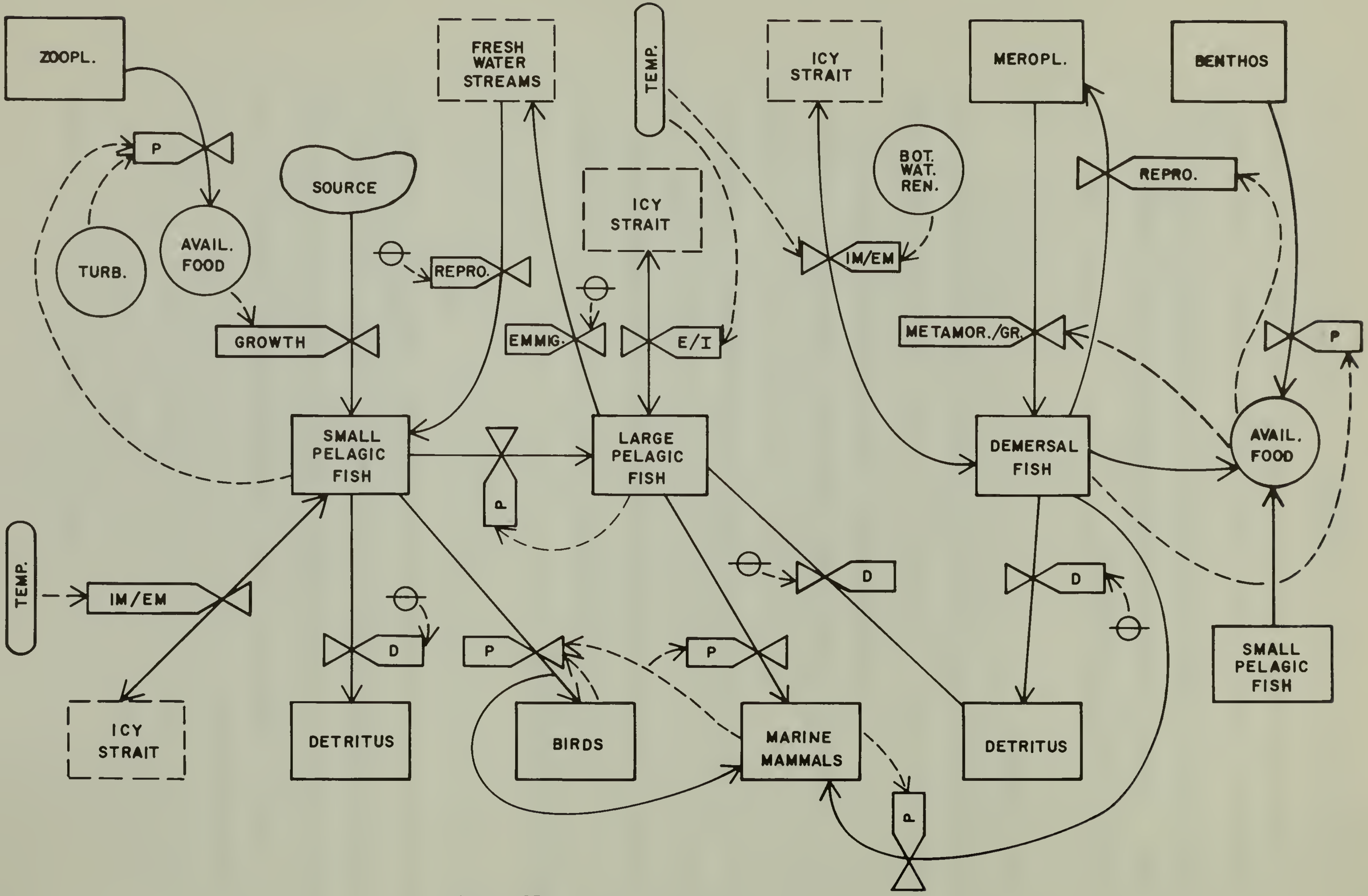


Figure 25.
GLACIER BAY ECOLOGICAL MODEL
FISH SUBMODEL

Pelagic Fish

Small pelagic schooling fish concentrate plankton resources and serve as food for numerous larger animals including humpback whales (especially during June and early July; C. Jurasz, personal communication), larger fish, seals and several species of birds.

Capelin *(Mallotus villosus)*, sand lances *(Ammodytes hexapterns)* and occasionally eulachon or hooligan *(Thaleichthys pacificus)* are abundant in lower Glacier Bay during the spring and summer. Pelagic fish distribution in the upper Bay is not known, but numbers are probably low. The winter habits of capelin are not known. Pacific herring *(Clupea harengus pallasi)*, a commercially important pelagic fish found in many parts of Southeast Alaska, has not been seen with any regularity or abundance in Glacier Bay. Wing (personal communication) suspects that capelin, an ecological equivalent of herring but found in more Arctic environments, is favored in the cold waters of Glacier Bay.

Salmon escapement surveys have infrequently been carried out by the Alaska Department of Fish and Game on the streams feeding Glacier Bay. Good runs and escapements are reported for the Bartlett River and for streams entering Berg and Fingers Bay. Anadromous fish runs can be expected to expand into the upper Bay as ecological succession within Glacier Bay continues.

Demersal Fish

Demersal fish are important predators on the benthic community. The extent to which Glacier Bay's demersal finfish population stay only within the Bay is not known but movements across the Glacier Bay sill to and from Icy Strait probably occur with some regularity.

Exploratory fishing trawls were undertaken throughout much of Glacier Bay in March of 1954 (See Data Appendix). The fish most commonly taken are listed in Table 5. A single fish trawl was taken in Icy Strait in September 1969; results are shown in Table 6, (Carlson et al., 1977). From observations of Southeast Alaskan fish populations, Dr. Jay Quast of the NMFS' Auke Bay Laboratory (personal communication) suspects that Glacier Bay's demersal fish population represents a colder water fauna than is found in other Southeast Alaskan inland waters.

The only demersal fish taken commercially in Glacier Bay is halibut. A generalized representation of its life cycle is shown in Figure 26. Halibut are strong swimmers and carnivorous feeders, eating almost any food they can catch. Larval halibut feed on plankton, whereas halibut 1 to 3 years old, that usually are less than 30 cm (12 inches) long, feed on small shrimp-like organisms and small fish. As halibut increase in size, crabs and fish become a more important part of the diet. The species of fish frequently observed in stomachs of large halibut include cod, sablefish, pollock, rockfish, sculpins, turbot, and other flatfish. Halibut often leave the bottom to feed on pelagic fish such as sand lance and herring (IPHC, 1978).

Anadromous Fish

All five species of Alaskan salmon (Table 7) plus Dolly Varden and cutthroat trout are found in lower Glacier Bay. Anadromous fish pass

Table 5--Common Animals Taken by Exploratory Fishing Drags. March, 1952 (NMFS, 1970).

Inlet	Animals most common in catch
Hugh Miller	Pollock, Pink Shrimp, Rock Sole
Queen	Pollock, Pink Shrimp, Side-strip Shrimp
Rendu	Tanner Crab, Pink Shrimp
Geike	Pollock, Pink Shrimp, Coon stripe Shrimp, Side-stripe Shrimp, Tanner Crab
Muir	Side-stripe Shrimp, Pink Shrimp, Tanner Crab, Pollock
Lower Glacier Bay	Pollock, Skates, Pink Shrimp, Side-stripe Shrimp, English Sole, Flathead Sole, Tanner Crab

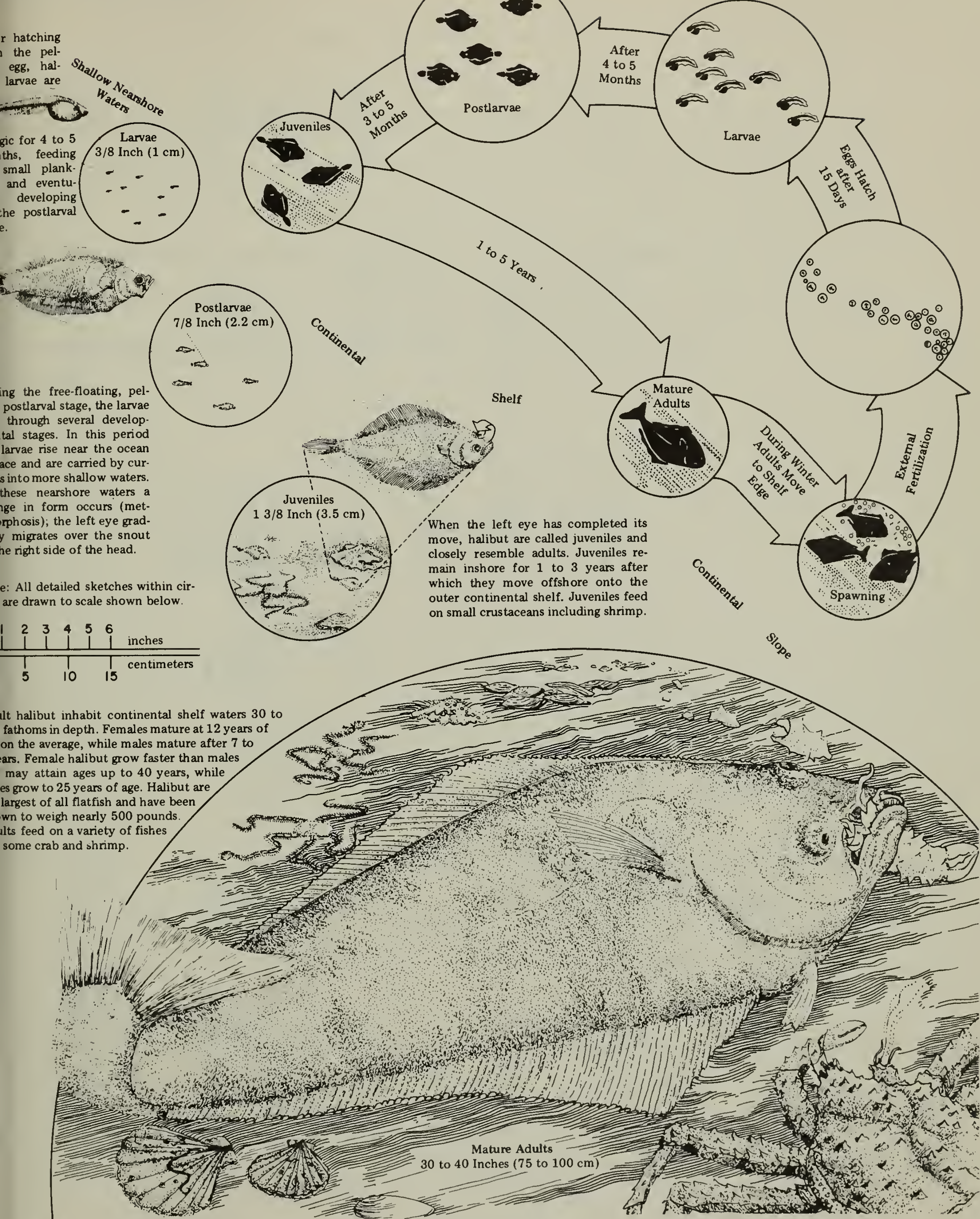
Table 6--Trawl Catch in Icy Strait September, 1969. Icy Strait off Southeastern Pleasant Island, September 1969 (Carlson *et al.* 1977).

Date	Depth Range (m)	Total Hauls	Total Bottom min	Mean Catch in 10 min lb (kg)	Mean weight of organisms in 10-min drag (lb)				
					Flatfish	Gadids	Rockfish	Other fish	Invertebrates
Sept 69	90	1	45	44.0	15.4	--	T	15.4	13.2
				(20.0)	(7.0)	--	(T)	(7.0)	(6.0)

Description of Catch

We made a single trawl haul off the southeast end of Pleasant Island in Icy Strait during September 1969, and the catch consisted of roughly equal amount of flatfishes, other fishes, and invertebrates (Table 6). Of the flatfishes, flathead sole and arrowtooth flounder made up the bulk; rex sole were taken incidentally. A variety of other fishes were present, which included the longnose and starry skates (*Raja rhina*) and *Raja stellulata*), spinyhead sculpins, Irish lords, young sablefish, juvenile dusky and rougheye rockfish, searchers, ronquils, snailfish (*Liparidae*), and eelpouts (*Lycodes sp.*). The invertebrates were mostly tanner crab and whelks (*Neptunea*) with pink shrimp, clams, and the hermit crab *Pagurus ochotensis* also present.

ALIBUT LIFE CYCLES



r hatching
the pel-
egg, hal-
larvae are

gic for 4 to 5
ths, feeding
small plank-
and eventu-
developing
he postlarval
e.

ing the free-floating, pel-
postlarval stage, the larvae
through several develop-
tal stages. In this period
larvae rise near the ocean
ace and are carried by cur-
s into more shallow waters.
these nearshore waters a
nge in form occurs (met-
rphosis); the left eye grad-
y migrates over the snout
he right side of the head.

When the left eye has completed its move, halibut are called juveniles and closely resemble adults. Juveniles remain inshore for 1 to 3 years after which they move offshore onto the outer continental shelf. Juveniles feed on small crustaceans including shrimp.

e: All detailed sketches within cir-
are drawn to scale shown below.

lt halibut inhabit continental shelf waters 30 to
fathoms in depth. Females mature at 12 years of
on the average, while males mature after 7 to
ears. Female halibut grow faster than males
may attain ages up to 40 years, while
es grow to 25 years of age. Halibut are
largest of all flatfish and have been
wn to weigh nearly 500 pounds.
lts feed on a variety of fishes
some crab and shrimp.

rce: E. H. Buck, et al. *Kadyak: A Background for Living.* Arctic Environmental
nformation and Data Center, University of Alaska. 1975.

Table 7--General life history features of the five species of Pacific salmon in Alaska. (Exceptions to these general descriptions occur frequently) (Hartman 1971).

Species of salmon	Freshwater habitat	Time spent in fresh water after emergence from gravel	Time spent at sea (years)	Year of life at spawning	Average weight of adults. (lb)	Average eggs per female (thousands)
Sockeye	Short streams and lakes	12-48 months	1-3	3-6	6	3.5
Pink	Short streams	Usually less than 1 day	1	2	4	2.0
Chum	Short and long streams	Less than 1 month	2-4	3-5	8	3.0
Coho	Short streams	12-24 months	1-½	3-4	9	3.5
Chinook	Large rivers	3-12 months	1-4	3-6	20	4.0

through Glacier Bay twice during their life cycle: as young on their way out to sea and as adults returning to home streams to spawn. A small population of King salmon are found year-round in Glacier Bay. The feeding juveniles which prey heavily on zooplankton and enriched detritus, and form an important food resource for larger organisms probably have a more significant impact on the marine ecosystem than do the adults. Large groups of feeding juvenile pink and chum salmon are often observed in lower Glacier Bay during the spring and summer.

Glacier Bay supports a large year-round population of harbor seals, a significant seasonal population of humpback whales, less abundant seasonal killer whale populations, occasional minke whales, and a harbor porpoise population whose seasonal pattern is not well known. These large mammals are among the most important species in Glacier Bay in terms of visitor interest. The occasional view of a breaching humpback or a pod of killer whales, and the more common sighting of resting harbor seals ranks among the high points of a visitor's experience at Glacier Bay. A discussion of the potential impacts that vessel and aircraft traffic in the Monument have on these species is found in the section on Vessel and Aircraft Traffic.

Because of the difference in their ecological functions and the information available, each of the major species will be discussed separately, and depicted in different submodels as shown in Figure 27.

Harbor Seals

Harbor seals (Phoca vitulina) are found along the U.S. Pacific Coast from Southern California to the Bering Sea. Glacier Bay supports one of the more sizeable seal populations in Southeast Alaska and has significant pupping grounds in Muir and Johns Hopkins Inlets. The Glacier Bay seal population has been censused and observed by Greg Streveler, Glacier Bay Research Biologist, since 1972 with more detailed studies beginning in 1975. The following information, except where noted, is abstracted from his detailed preliminary report (1978).

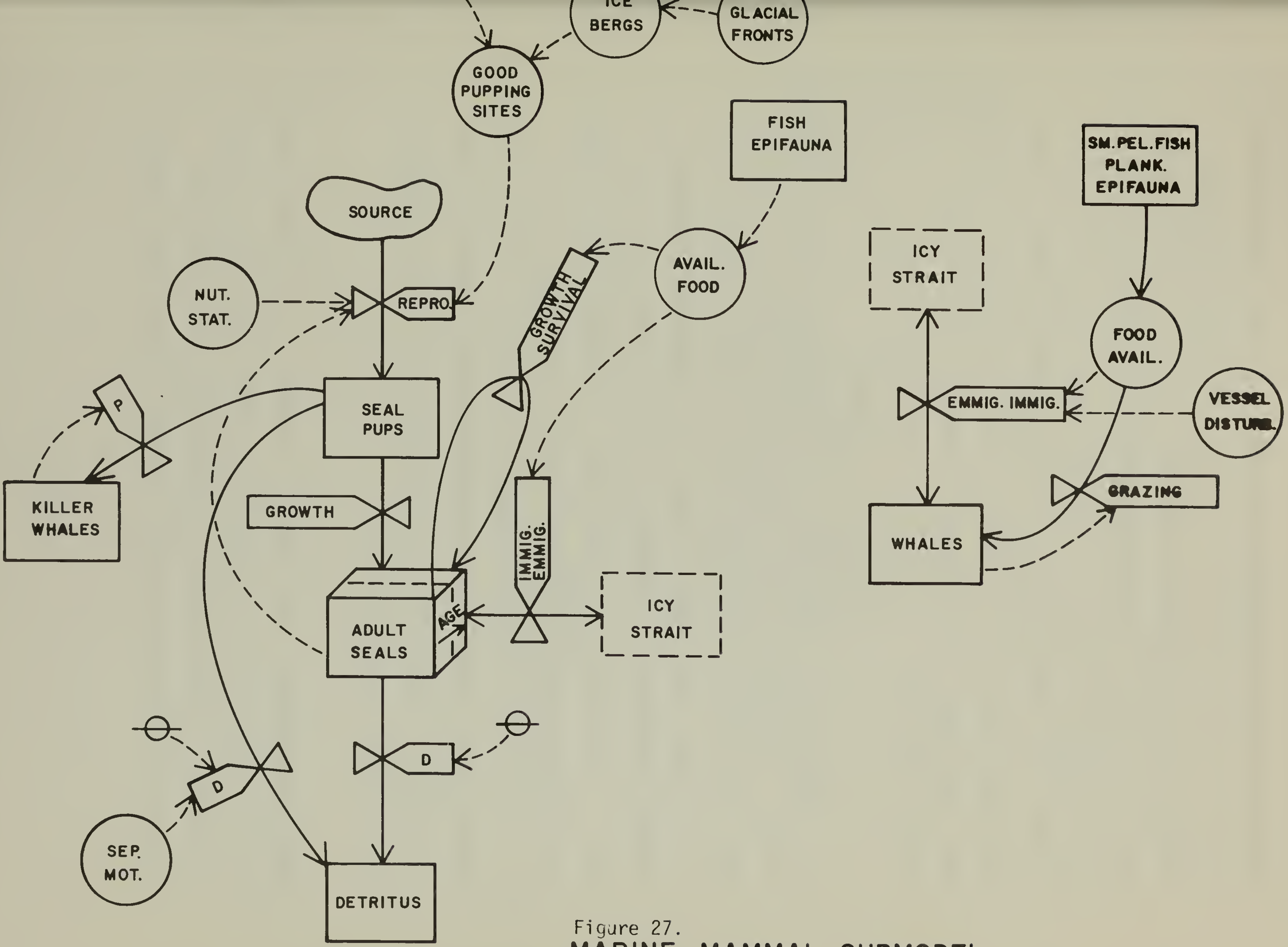


Figure 27.
MARINE MAMMAL SUBMODEL

Population size and distribution: The Glacier Bay seal population has been fairly stable over the last three years with about 1400 winter residents and over 4000 summer inhabitants (Table 8). Although harbor seals are not considered migratory, considerable movement occurs in response to reproductive activity, prey concentration, and climate (Pitcher, 1977). Neither the reasons for the seasonal changes in seal abundance nor the wintering grounds of many summer Glacier Bay seals are known, but as shown in the submodel, is probably in part related to available food supply.

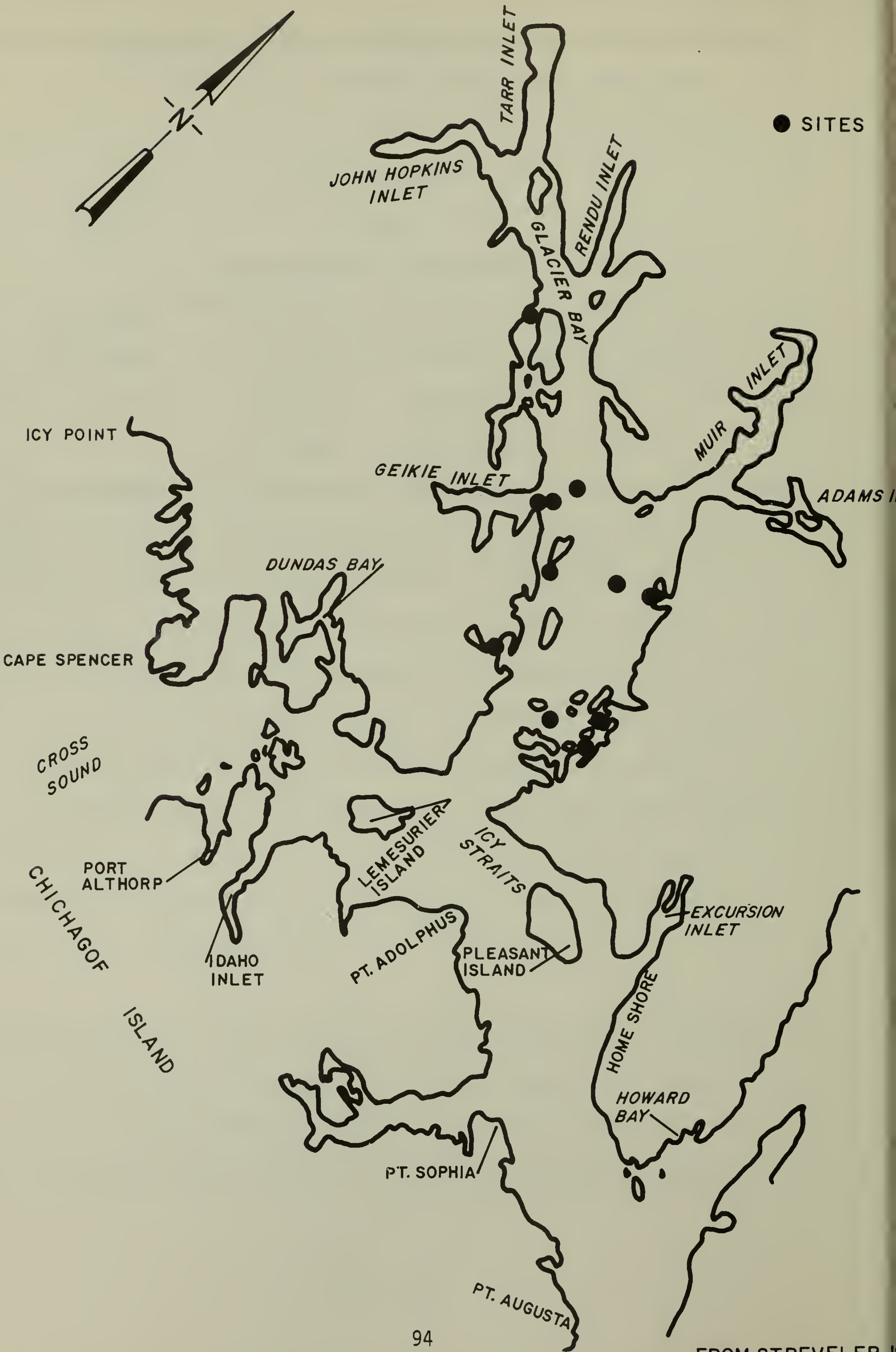
The spatial distribution of harbor seals in Glacier Bay changes throughout the year. In April or early May when the pan ice goes out of the upper inlets, seals begin to concentrate in the Muir and Johns Hopkins Inlet pupping grounds. Seal numbers in these inlets continue to increase throughout the summer with maximum populations probably occurring in August. In mid-July, molting seals begin to congregate in large groups (up to 100 individuals) on rocks and inlets in mid-Glacier Bay (Fig. 28). By September the large aggregates start to dispand and some seals leave the Bay. By November, the winter population is stable and seals are dispersed in sheltered locations throughout the Bay and at the edge of the pan ice in the upper Inlets.

Population Parameters: Harbor seals in Icy Bay, to the north of Glacier Bay begin reproducing at about age 5 or 6, males attain sexual maturity at about age 7 (Pitcher, 1978). Throughout most of its range, the harbor seal gives birth to its pups on land, on sandy beaches, remote

Table 8--Harbor Seal Population Estimates Glacier Bay, Alaska (adapted from Streveler 1978).

Year	Number of Seals		
	Summer		Winter
	pre-pupping	post-pupping	
1972			1392-1856
1974			1337-1782
1975	3583-4229	4217-4863	
1976	2963-3360	3784-4181	
1977	3674-4119	4743-5188	1400-1866

Figure 28. MAJOR HARBOR SEAL HAUL-OUT SITES



FROM STREVELER

reefs and rocks along the coast. In Glacier Bay the great majority of pupping occurs on icebergs. Consequently, over the years as ice conditions have changed, the location of the Bay's major pupping grounds have also changed. Presently, the most important pupping areas are the icebergs found in Upper Muir and Johns Hopkins Inlets. Small numbers of seal pups are also born on the shores of the Beardslee Islands and Hugh Miller Inlet.

Streveler has estimated the number of births within Glacier Bay from 1975 to 1977 (Table 9) and computed an average natality rate of about 21%. Mortality rates are estimated to be approximately equal to natality.

Food Habits: Seal feeding has not been systematically studied in Glacier Bay. Work done in other areas of Southeast Alaska (Imler and Sarber, 1947) and in the Gulf of Alaska (Pitcher 1977, 1978) shows that seals prey on a variety of food types with demersal fish (especially cod and flounder), near bottom fish (pollock), schooling pelagic fish (herring and smelt) and in certain areas, shrimp, frequently being the dominant prey. Streveler has observed Glacier Bay seals commonly feeding near concentrations of schooling smelt and sandlances during the spring and, in summer, has seen seals surface with flounder, codfish, and salmon. These fish are probably not abundant in upper Glacier Bay where the pupping seals congregate. Alternate food resources for the Muir Inlet and Johns Hopkins seals are shrimp and pollock. Although the nutritimal status of pregnant and nursing females clearly affects reproduction and pup survival, there are no data on this relationship. The extent of feeding by nursing mothers is not known.

Table 9--Natality Estimates for Harbor Seals Glacier Bay, Alaska (Streveler 1978).

Locality	1975	1976	1977
Johns Hopkins	359[1] + 36[2]	551 + 55	685 + 69
Muir	189 + 23	142 + 17	207 + 25
Rest of Bay	21 + 6	44 + 12	62 + 21
	634	821	1069
% of Total post-pupping population	13-15%	20-22%	21-23%

[1] Pups counted

[2] Estimate of unborn pups at the time of the count

Ecological Role: With the exception of occasional killer whale predation, seals are relatively free from predation in Glacier Bay. The importance of seal nutrient (nitrogen, phosphorus) contributions to the waters of Muir and Johns Hopkins Inlets is not known but may be significant.

Humpback Whales

The humpback whale (*Megaptera novaeangliae*), a cosmopolitan species probably composed of discrete populations, was classified as an "endangered" species in 1970. About 60 individuals are thought to summer in Southeast Alaska, with up to one-third of them spending considerable time periods in Glacier Bay. The Glacier Bay humpbacks have been observed and censused by Charles and Virginia Jurasz since 1973, with more detailed studies, particularly on individual identification, whale to whale, and whale to vessel interactions starting in 1976. All of the information in this section is based on their work as described in Jurasz and Jurasz (1978 and 1978) and in verbal discussions.

Population Size and Distribution: The Glacier Bay whale population began to increase in the early 1970's, possibly as a result of whales being displaced from the Juneau area. The numbers of whales censused in Glacier Bay in 1976, 1977 and 1978 is shown in Table 10. Whales enter Glacier Bay in two influxes. The first begins in late May or early June, and the second in July, usually coincident with large euphausid populations becoming visible in the surface waters. The second influx is usually larger than the first. By mid to late August, the whales leave Glacier Bay. The winter location of Glacier Bay's whales is not

Table 10--Humpback Whale Population Glacier Bay, Alaska (Jurasz and Jurasz 1978).

	Number of Humpback Whales		
Year	First Influx	Second Influx	Seasonal Maximum
1976	9	11	20
1977	7	17	24
1978	14*	6*	24*

* Preliminary figures from C. Jurasz, personal communication

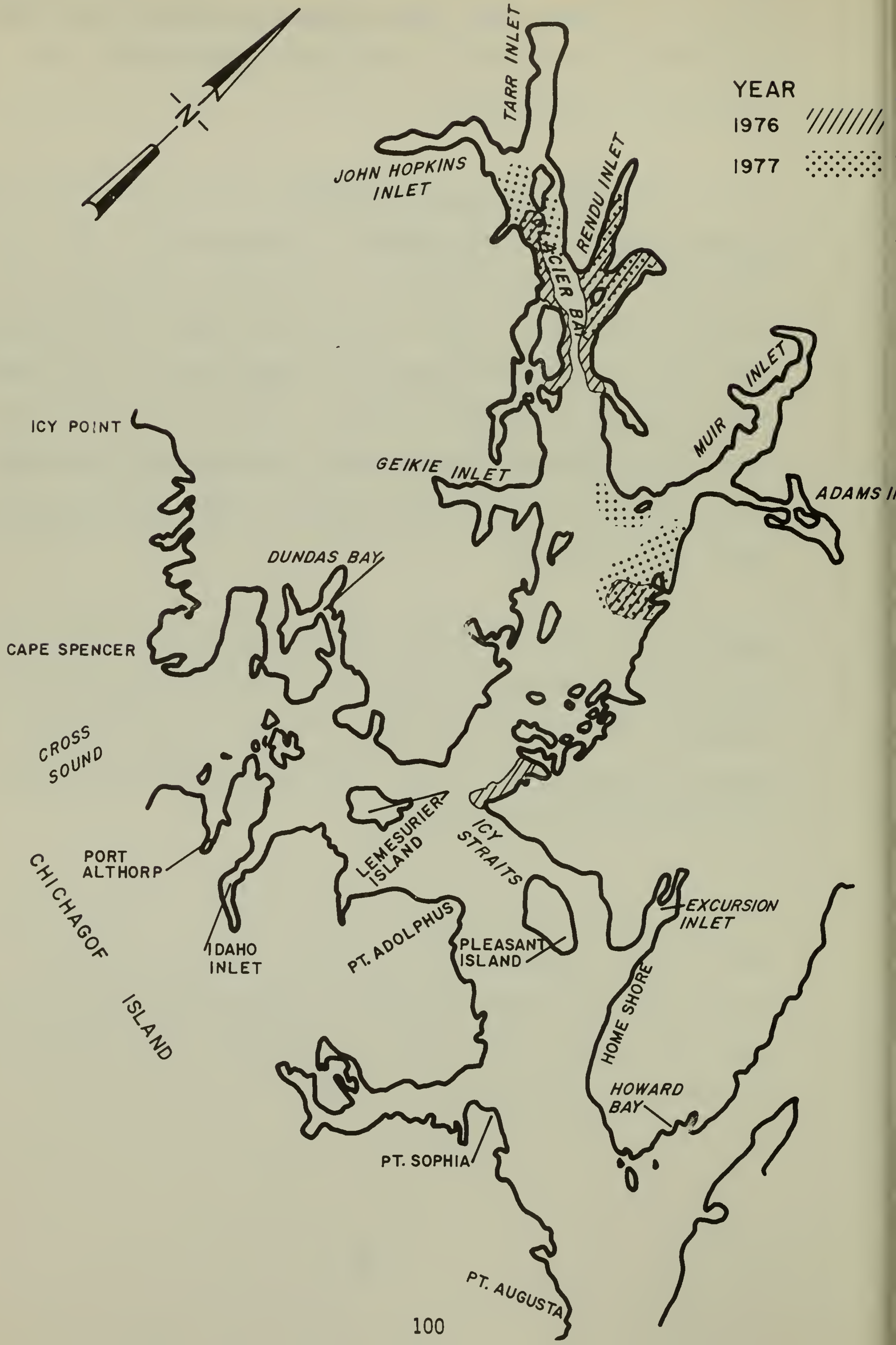
known with certainty, but C. Jurasz suspects that the population stays in Southeast Alaska perhaps in lower Stephens passage around Cape Fanshaw and in Seymour Canal.

The use of Glacier Bay by the humpback whales during the summer of 1978 was very different than the previous two years, and the Juraszes' suspect that this may be due in part to displacement of the whales by vessels. By early July, about 14 whales were present -all in the Bartlett Cove area, then in mid-July, there was a sudden collapse of the population from 14 to three animals within 48 hours. For the rest of the summer only about six animals frequented the Bay. Several (possibly three) animals which were in Glacier Bay in early July were later seen in the waters off Cape Fanshaw.

Whales preferentially use specific parts of Glacier Bay. Areas most frequented by humpbacks were generally the same both geographically and seasonally in 1976 and 1977 (Fig. 29). The first influx of animals generally frequents the lower Bay. With the second influx, the population shifts towards the middle Bay.

In 1978, the use of these habitats changed somewhat. Although whales were still seen feeding in these areas, they more often behaved as transient rather than resident animals. During the first half of July, many of the "Bartlett Cove" whales were observed to also spend time in Icy Strait and Cross Sound.

Figure 29. **CRITICAL HABITAT FOR HUMPBACK WHALES**



The Jurasz's have been able to document the return of about a half dozen individual whales to Glacier Bay over the last two years and three individuals for three years.

Food Habits: Feeding appears to be a major activity of humpback whales in Glacier Bay. It is probably more than coincidence that whales enter Glacier Bay during the peak of its production. Juraszs' observations indicate that the first influx of whales feed primarily on schooling pelagic fish (mostly capelin) found in lower Glacier Bay. Beginning in July, shrimp become a significant food source, particularly in the upper Bay around Composite Island. From mid-July through August, krill (euphausids) become the whale's primary food source. Towards the end of the summer shrimp again become an important food item. The relationship of feed and whale distribution received some preliminary attention from the Juraszs' in their early studies but since then has not been examined in detail. Additional work on this critical relationship is necessary to fully interpret the Juraszs' population and whale displacement data.

The submodel for humpback whales is simple, reflecting their limited use of the Bay for feeding and resting during the summer season. Many of the major elements of their life cycle, including reproduction, occur outside Glacier Bay and consequently are not included in the diagram. There are no records of humpback whales dying in Glacier Bay; their contribution to the detritus cycle is unknown.

Birds are often in attendance when whales are feeding, with different species present with each kind of feed. When pelagic fish are the feed, gulls, murrelets, and puffins are typically in attendance; with drill as the feed, murrelets and phallaropes are found; and with shrimp as the feed, only black guillemots are found. The birds are undoubtedly taking advantage of the whales as concentrators of food.

Killer Whales

The killer whale (Orcinus orca) has a world wide distribution with greatest abundance in cold waters. Small pods of killer whales are seen in Glacier Bay primarily in late May and again in late August, although Streveler (personal communication) reports occasional sightings year round. These carnivores are known to take seals and large fish.

Harbor Porpoise

The harbor porpoise (Phocoena phocoena) is a little studied inhabitant of both the Atlantic and Pacific Coast. Its food consists mainly of fish and occasionally invertebrates (Brooks, 1978). Jurasz counted 68 during the summer of 1978 with the most sightings in Sitakaday Narrows, Hugh Miller Inlet and in the environs of Composite Island. Much more work is necessary to establish reliable population estimates and distribution patterns within Glacier Bay.

BIRDS

Glacier Bay's rich and abundant bird life is a focus of both visitor and ecological interest. In a functional sense, birds can be thought of as concentrators and transporters of organic material both within Glacier Bay and to areas outside the Bay. The degree to which this role is true for a particular species largely depends on its feeding and nesting habits, and its abundance within the system.

Over the years, Glacier Bay's bird population has been observed by Monument personnel; and bird species, numbers, and locations are relatively well known. Much less is known about bird feeding habits and their effects on the marine ecosystem. Except where noted, the information below is based on conversations with Bruce Paige, Glacier Bay National Monument Chief Naturalist.

The seasonal abundance of the more common birds found in Glacier Bay is shown in Table 11. For more complete information see Paige (1973) and Wik (1967).

Bird Submodel

Three different types of bird populations can be found in Glacier Bay over the yearly cycle, migrants, winter residents, and nestors. These three categories are reflected in the bird submodel illustrated in Figure 30.

Migratory Birds: Hundreds of thousands of birds migrate through Glacier Bay during the spring and fall. Waterfowl, cormorants, loons, arctic terns, Bonaparte's and other gulls, alcids and numerous shorebirds make up the bulk of the migrants.

Table 11 - Common Birds of Glacier Bay (Paige, 1973 and personal communication)

Key
A - Abundant R - Rare
C - Common V - Very Rare
F - Fairly Common
U - Uncommon

	Spring	Summer	Fall	Winter	Comments
Common loon[1]	F	F	F	F	peak populations in Sp/Fall; 10,000 - 20,000, fish eaters
Horned grebe	C	V	C	C	eat fish, some shrimp
Pealgic Cormorant	C	C	C	F	about 200-500 pairs in the Bay, eat fish
Canada Goose	C	F	C	C	important molting areas in Bay
Puddle Ducks	C	F	C	C	surface feeders
Mallard	F	R	F	R	
Pintail	F	R	F	U	
Green-winged Teal	C	R	C	U	
American Widgeon	C	R	C	U	
Diving Ducks					fish and shellfish feeders
Barrow's Goldeneye	A	U	A	A	
Old Squaw	C	R	C	A	10,000 - 20,000 in Bay during winter, deep divers
White-winger Scoter	C	F	C	C	
Surf Scoter	A	C	A	A	80% of all Scoters, have flightless period
Bufflehead	C	R	C	C	
Mergansers					
Common	C	F	A	U	more common in summer
Red Brested	C	R	C	C	more common in winter
Bald Eagle	C	C	C	C	
Shorebirds					mostly transients, more in spring than fall
Black Oystercatcher	F	F	F	V	
Spotted Sandpiper	F	F	F	-	
Rock Sandpiper	R	-	R	F	
Northern Phallarope	U	A	C	-	hundreds of thousands, plankton feeders

Common Birds of Glacier Bay (cont.)

	Spring	Summer	Fall	Winter	Comments
Gulls and Terns					
Glaucous Winged Gull	C	C	C	F	highest number in summer (20,000), open waters
Mew Gull	C	F	C	C	dispersed in summer (10,000)
Bonaparte's Gull	F	R	A	-	feed at surface
Black-legged Kittiewake	F	F	F	-	feed at tidewater glacier face
Arctic tern	F	F	U	-	several thousand in summer
Sea Birds					
Common Muerre	F	R	F	A	100,000 in winter (includes Icy Strait)
Pigeon Guillemot	F	C	F	U	most common seabird nester in Bay
Marbled Murrelet	F	C	F	F	50,000, fish eater
Kittlitz's Murrelet	U	F	R	-	50,000, fish eater

---

[1] scientific names of all the birds listed are included in the Data Appendix

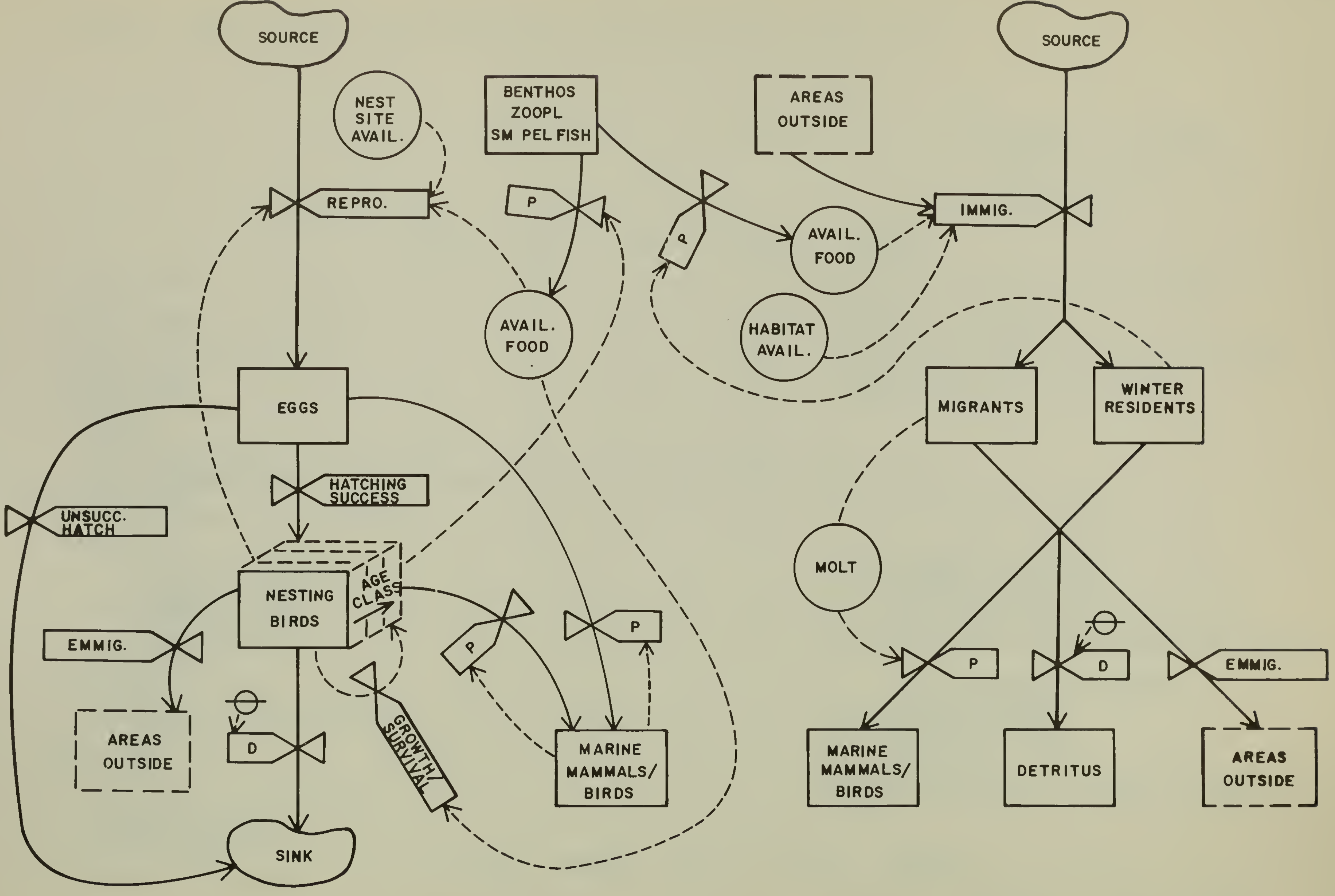


Figure 30.
GLACIER BAY ECOLOGICAL MODEL

BIRD SUBMODEL

Spring influxes begin in mid to late March, peak in May and by mid-June residents out number transients. By mid-July the first of the southbound migrants enter Glacier Bay; by the end of September most migrants have left.

The migrating geese and puddle ducks concentrate in Hugh Miller and Adams Inlets and around Gustavus; the loons in Geike and Adams Inlets and the shorebirds on all the Bay's rocky and sandy shores with large concentrations found along the shores of Hugh Miller and Adams Inlet, the Beardslee Islands and the mudflats adjacent to Seabree Island. Perhaps the most abundant migrating species that uses Glacier Bay is the northern Phalarope. Beginning in July hundreds of thousands of these largely plankton feeding birds are found in rafts near tide rips, around floating masses of seaweed, and in the vicinity of whales and schools of fish.

Winter populations: During the winter, Glacier Bay supports important concentrations of water-dependent birds. The winter population consists primarily of fish and shellfish-feeding common murres and other alcids, diving ducks (principally old squaw, Barrow's goldeneye, surf and white winged scoters and bufflehead), horned grebes, red breasted mergansers, and mew and glaucous-winged gulls. The only shorebird common in Glacier Bay during the winter is the rock sandpiper.

The winter distribution of birds shows a larger porportion of the total population in the open water areas than at other times of year. While scoters and red-breasted mergansers, horned grebes and other species are found in sheltered areas, especially Adams and Hugh Miller Inlets and the Beardslee Islands, the much more abundant old squaws and common murres are found in the open waters of mid-Glacier Bay and Tarr and Muir Inlets.

In terms of their influence on or by other elements of the Glacier Bay marine ecosystem, both migrant species and winter residents can be treated in much the same manner. The choice of using Glacier Bay, whether for a brief stopover by migrants or for the entire winter season, is generally influenced by the availability of food, habitat, and other suitable areas outside the Bay.

Nesters: The nesting birds in Glacier Bay include both year round residents (such as bald eagles, glaucous-winged gulls, pelagic cormorants, common and red throated loons) and birds that breed in the Bay during the summer then leave for the winter (e.g. black legged kittiwakes, harlequin ducks and several shorebirds including black oyster catchers, semipalmated plovers and spotted sandpipers).

The colonial birds found on the small rocky islands and rock cliffs scattered throughout Glacier Bay are the most obvious nesters. The availability of such protected habitat may be a factor limiting the overall size of the Bay's nesting bird population.

Colonial birds concentrate organic material, and through their excretory products may aid in the concentration of nutrients in the waters adjacent to their colonies and consequently stimulate primary production (McRoy, 1974). By far, the most abundant colonial nester in Glacier Bay is the glaucous-winged gull. Many of the Bay's pelagic cormorants and pigeon guillemots, the most abundant nesting seabird in Glacier Bay, breed in the same locations as the gulls. There are black legged kittiewake colonies near the faces of Johns Hopkins and Margerie Glaciers. These gull-like birds take advantage of food brought to the surface by calving icebergs and meltwater rivers.

The breeding ecology of the glaucous winged gull colony on North Marble Island (500 pairs of nesting birds) was studied in some detail by Patten in 1972 and 1973 (Patten, 1974). Gull breeding success was high (68%) with most mortalities resulting from predation on eggs by other gulls, ravens, and crows. Chick mortality averaged 7% with bald eagles being the major predator.

DETRITUS

Detritus (dead and decaying organic material) is utilized as a food source for many animals both for its own nutritive value and for the micro-organisms which colonize it. For example, enriched detritus (detritus colonized by bacteria and protozoa) is an important food source for many species of zooplankton and, in winter, juvenile chum salmon. The importance of a detritus-based food chain in Glacier Bay is not known but may be significant, especially in winter.

Detritus/Nutrient Regeneration Submodel

The submodel illustrated in Figure 31 is based on general knowledge, as no work has been done on the introduction, decomposition, utilization or export of detritus in Glacier Bay. The relative importance of the Bay's sources of detritus - dead organisms and excretion products produced within the system, materials brought into the Bay from the surrounding land via freshwater input, and detritus brought in, over the sill, from Icy Strait -has not been studied. Detritus not utilized within the system - as food or decomposed to unorganic nutrients - or exported to Icy Strait becomes incorporated into the sediments (illustrated in the model as a sink).

Nutrient Regeneration: Nutrient regeneration is the process which most directly links the consumer submodels back to the primary production submodel. Nutrients are essential to primary production (see Fig. 22). In addition to nutrients regenerated within Glacier Bay, new nutrients

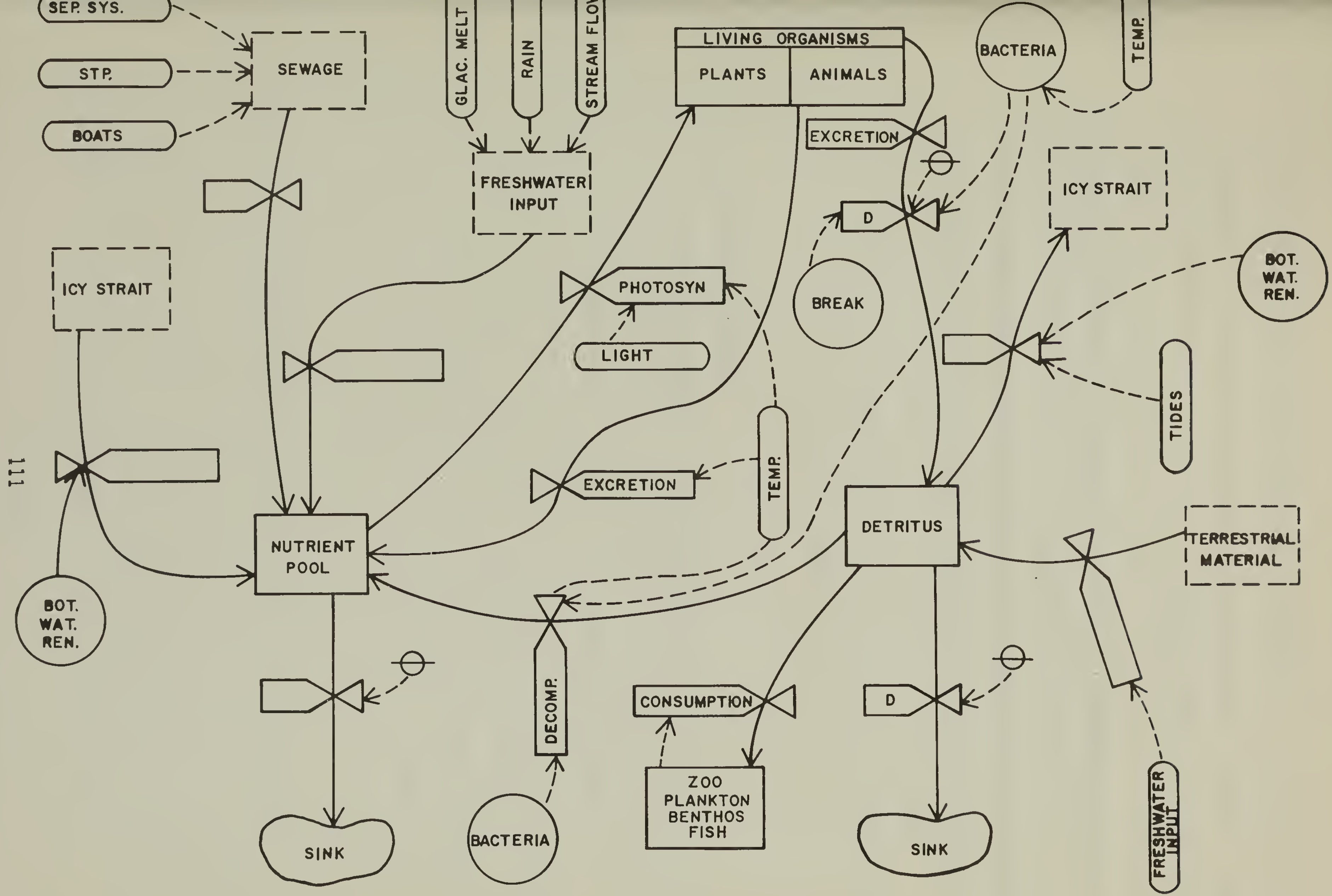


Figure 31.
DETRITUS / NUTRIENT REGENERATION SUBMODEL

are introduced into the Bay via freshwater and, much more importantly, deep, nutrient-rich marine waters that enter Glacier Bay through the process of deep water renewal.

Man has the potential to contribute significant quantities of nutrients to Glacier Bay via sewage disposal and altered land use patterns (see sections on Sewage Disposal and Mining); however, such sources are currently of negligible ecological significance to the system.

VISITOR'S EXPERIENCE OF GLACIER BAY

Glacier Bay National Monument is primarily a marine-based park. Nearly all visitors view Glacier Bay from the water (see the Vessel and Aircraft Traffic Section for details). However, a visitor's perception of the marine ecosystem of Glacier Bay is quite different from descriptions presented in the previous sections. The system components and processes most important to the visitor may be insignificant from an ecological perspective. Since Glacier Bay is in the National Park System the ecological system must be managed not only to preserve its own attributes, but also to provide for its use and enjoyment by the visitor.

Visitor Experience Submodel

The visitor experience submodel illustrated in Figure 32 is based on the authors' conversations with and observations of visitors in Glacier Bay National Monument during the summer of 1978. Visitor experience is considered as a subjective measure of the satisfaction gained by visitors on their trip to the Bay. The factors illustrated as affecting a visitor's experience represent only those directly associated with the marine system. Obviously, the total visitor experience includes much more.

Nearly all visitors experience the marine system during the summer through a boat ride. On that ride, the visitor may experience the force of tidal currents, the Bay's climate, as well as the majestic scenery of the surrounding landscape. Viewing the Bay's abundant animal life is a key element of the experience with whales, seals and unusual bird

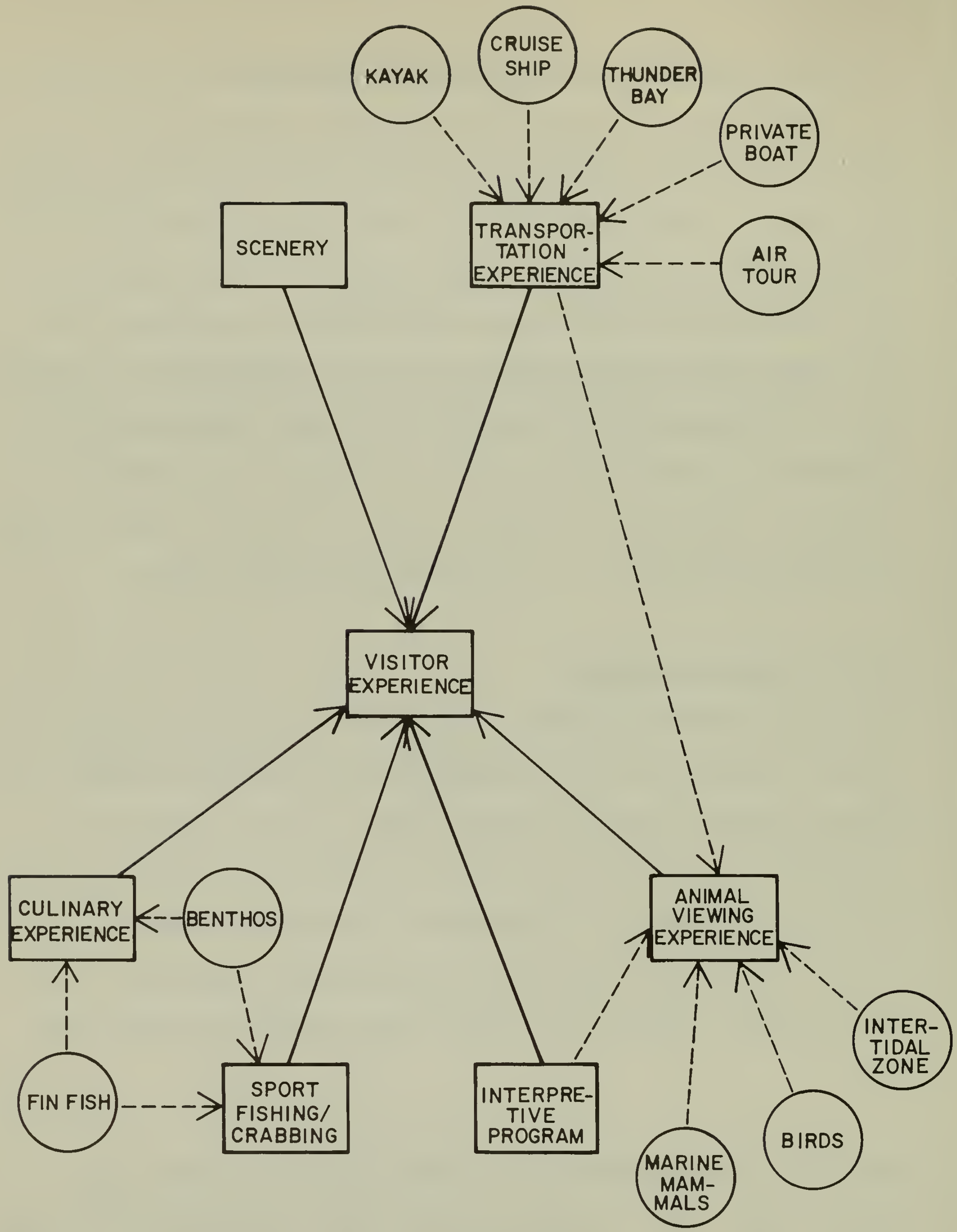


Figure 32. **VISITOR EXPERIENCE SUBMODEL**

species being of particular interest. A small number of visitors view the organisms of the Bartlett Cove intertidal zone on interpretive walks lead by Park Naturalists. The smaller, less conspicuous but ecologically important organisms such as plankton and benthic organisms are not presently part of the visitor's experience. Glacier Bay's finfish and shellfish populations are part of the visitor experience mainly through sportfishing which is undertaken by a proportionately small number of visitors, and by eating commercially harvested seafood at the Glacier Bay Lodge.

All elements considered in the submodel can presumeably enhance the visitor's experience, e.g., excellent weather, the sighting of large numbers of marine mammals or interesting birds; or they can detract from it, e.g., rainy foggy weather, a paucity of sightings, or rough water. Because of this, the construction of this submodel differs somewhat from the other submodels presented earlier in that all of the major flows can be in either direction.

SECTION III

A SUMMARY OF INFORMATION ON MAJOR HUMAN ACTIVITIES AT GLACIER BAY

COMMERCIAL FISHING

Commercial fishing activities occur throughout the year in lower Glacier Bay (Fig. 33). The finfish fishery is largely limited to halibut and salmon with most activity occurring from May to October. Crabbing goes on year-round with tanner and king crab caught in the winter and Dungeness crab in the summer. With the exception of halibut, which is managed by the International Pacific Halibut Commission, Glacier Bay's fisheries are managed and regulated by the Alaska Department of Fish and Game.

From a statewide perspective Glacier Bay is not a major fishing ground; however, from a regional perspective its halibut fishery is of growing significance.

Fishing pressure on Glacier Bay varies from year to year. Records of commercial fishing vessel visits to Glacier Bay are kept by park rangers, but these data (Fig. 34) are not always complete and are difficult to interpret. In terms of relative fishing pressure; however, the data, plus observations by the Glacier Bay National Monument staff suggest that the number of vessels regularly fishing Glacier Bay has decreased over the past two years. Unfortunately, the total catch is not known.

Finfish

Halibut: Commercial halibut fishing within Glacier Bay is carried out in the lower Bay by small vessels, less than 5 tons. A small amount of

FIGURE 33

COMMERCIAL FISHING ACTIVITY

GLACIER BAY

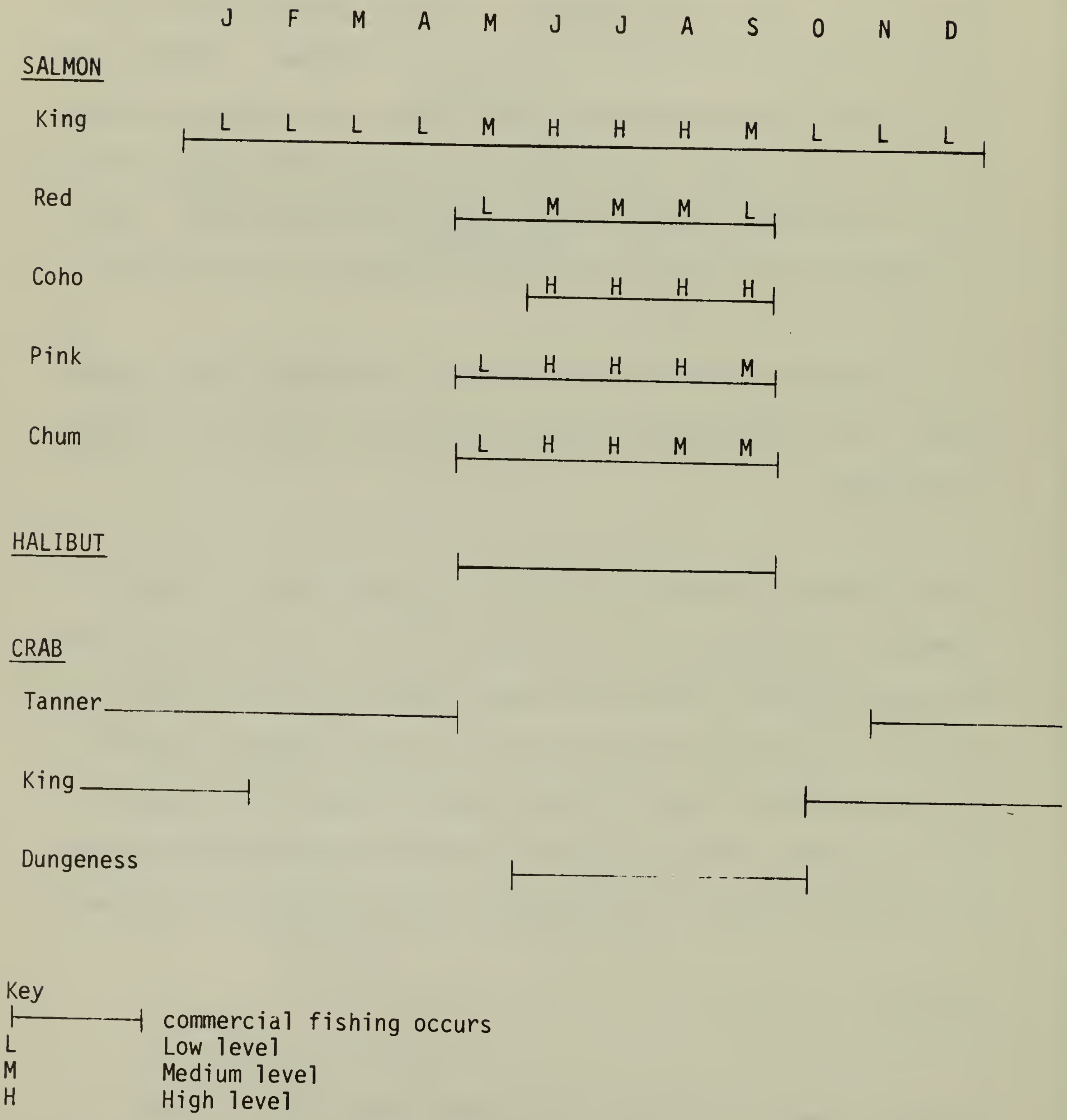
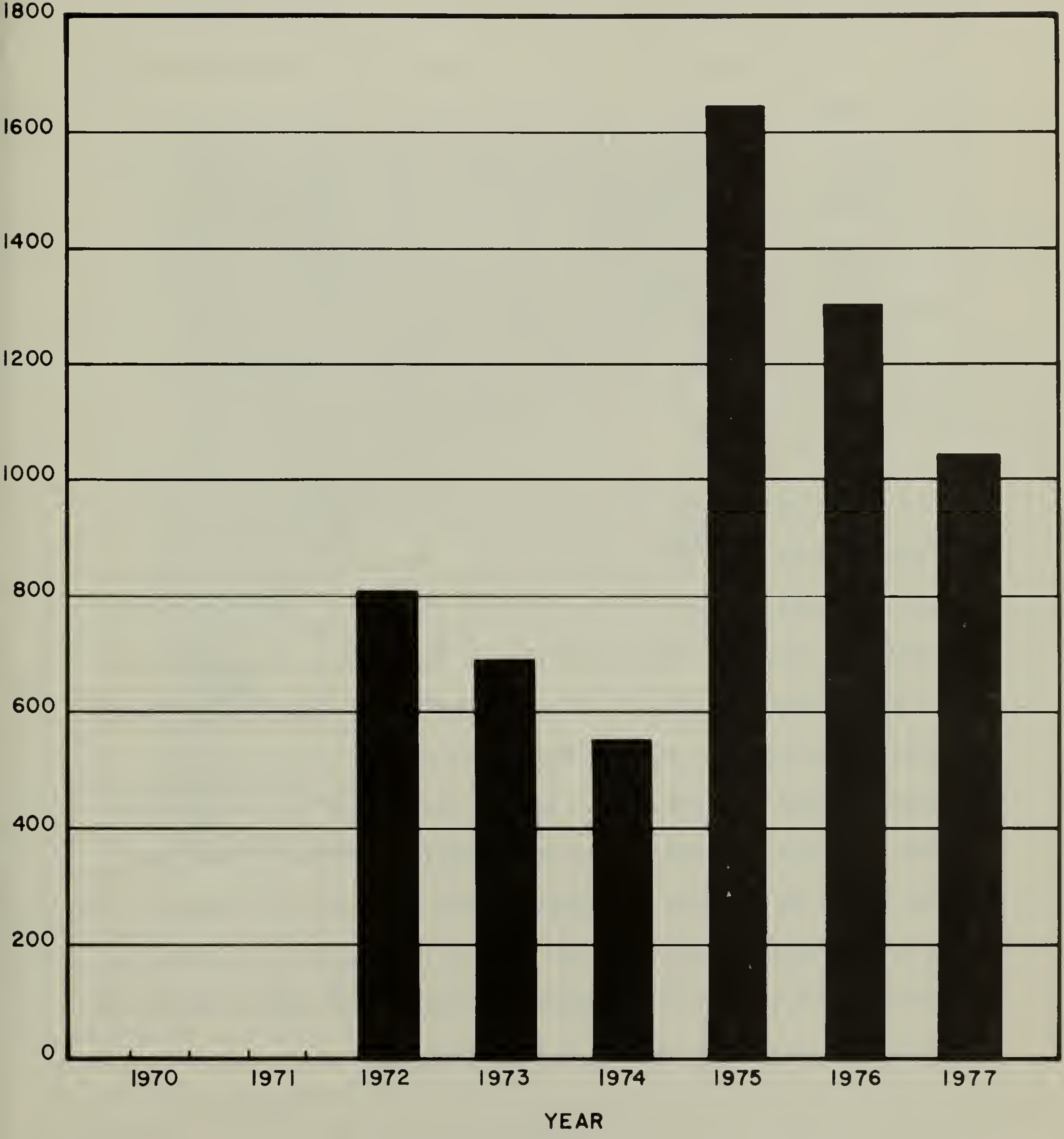


Figure 34. **COMMERCIAL FISHING VESSEL VISITS TO GLACIER BAY**



fish (approximately 900kg or 2,000 lbs/yr) is sold directly to the Glacier Bay Lodge (Peter Donau, Lodge Manager, personal communication) but most of the catch is landed at ports outside the Monument.

Neither the Glacier Bay halibut catch nor the characteristics of its halibut population is precisely known. In general, halibut spend the winter in offshore deep waters, then in summer move to shallower coastal waters. However, halibut within Glacier Bay could simply move from shallow to deep water within the Bay rather than moving outside the Bay. Fishermen fish Sitakaday Narrows, the sill to Glacier Bay, during the spring and fall (Mike Nigra, Glacier Bay National Monument Park Ranger, personal communication). This would indicate significant movement into and out of the system during the time the fish would be expected to migrate.

Glacier Bay is part of the International Pacific Halibut Commission's regulatory Region 2, statistical area 18 S-I, sub area 182 (Fig. 35). The halibut catch and catch per unit effort (C.P.U.E.), for these latter two areas are shown in Table 12 and Figure 36. C.P.U.E. is a measure of the relative abundance of halibut on the fishing grounds. Factors such as length of ground line and number of hooks used affect the C.P.U.E. Although sub-area 182 includes Icy Strait, the bulk of the catch, which in 1966 peaked at over two million pounds of fish, probably comes from Glacier Bay. The relative importance of this catch over the last 20 years to the region, state and total fishery is illustrated in Table 12. An average of 16 percent of the Southeast Alaska catch comes from Glacier Bay, and this percentage appears to be increasing.

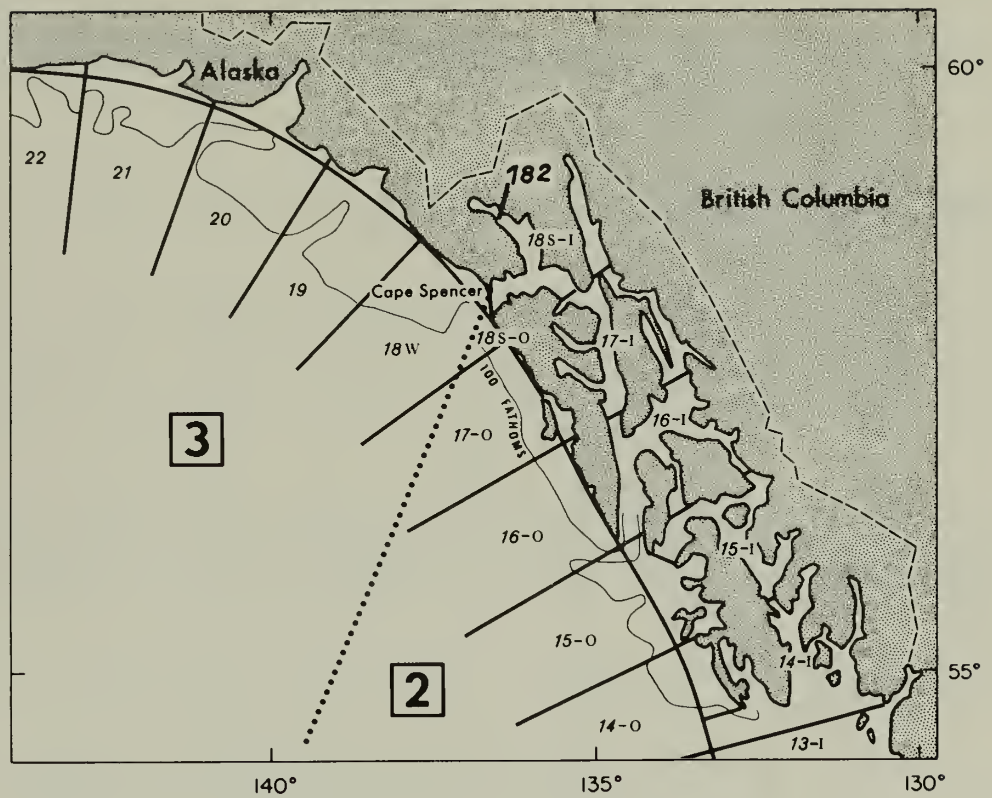


Figure 35. **Regulatory areas ☐ and statistical areas in southeastern Alaska** as designated by the International Pacific Halibut Commission (reproduced from Myhre, et. al., 1977)

Figure 36. Halibut **CATCH PER UNIT EFFORT**

1957 - 1977

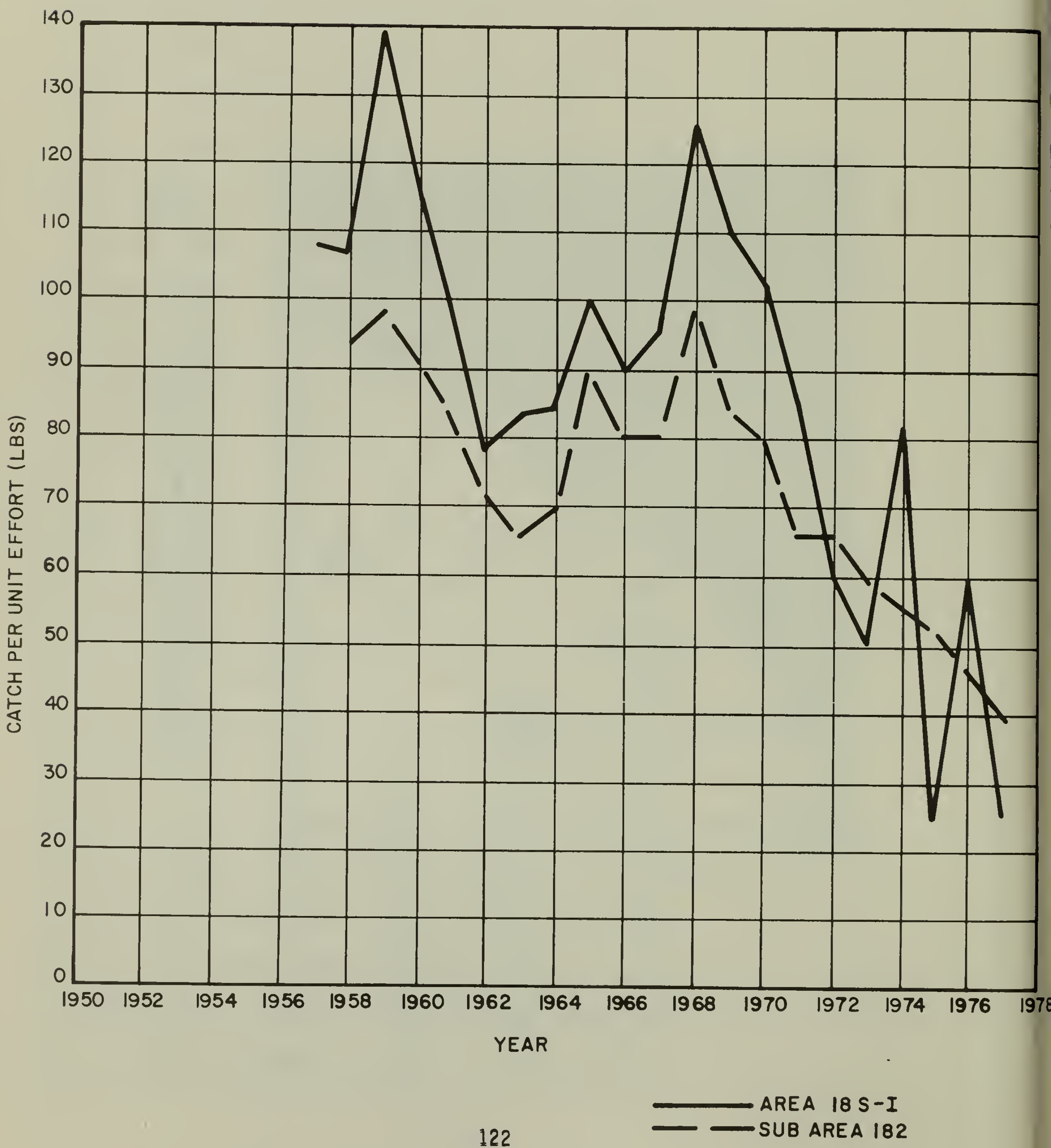


Table 12 - Halibut Catch (x 1000 lbs.) by statistical subarea, area, region, and country 1958-1978 (data from the International Pacific Halibut Commission.)

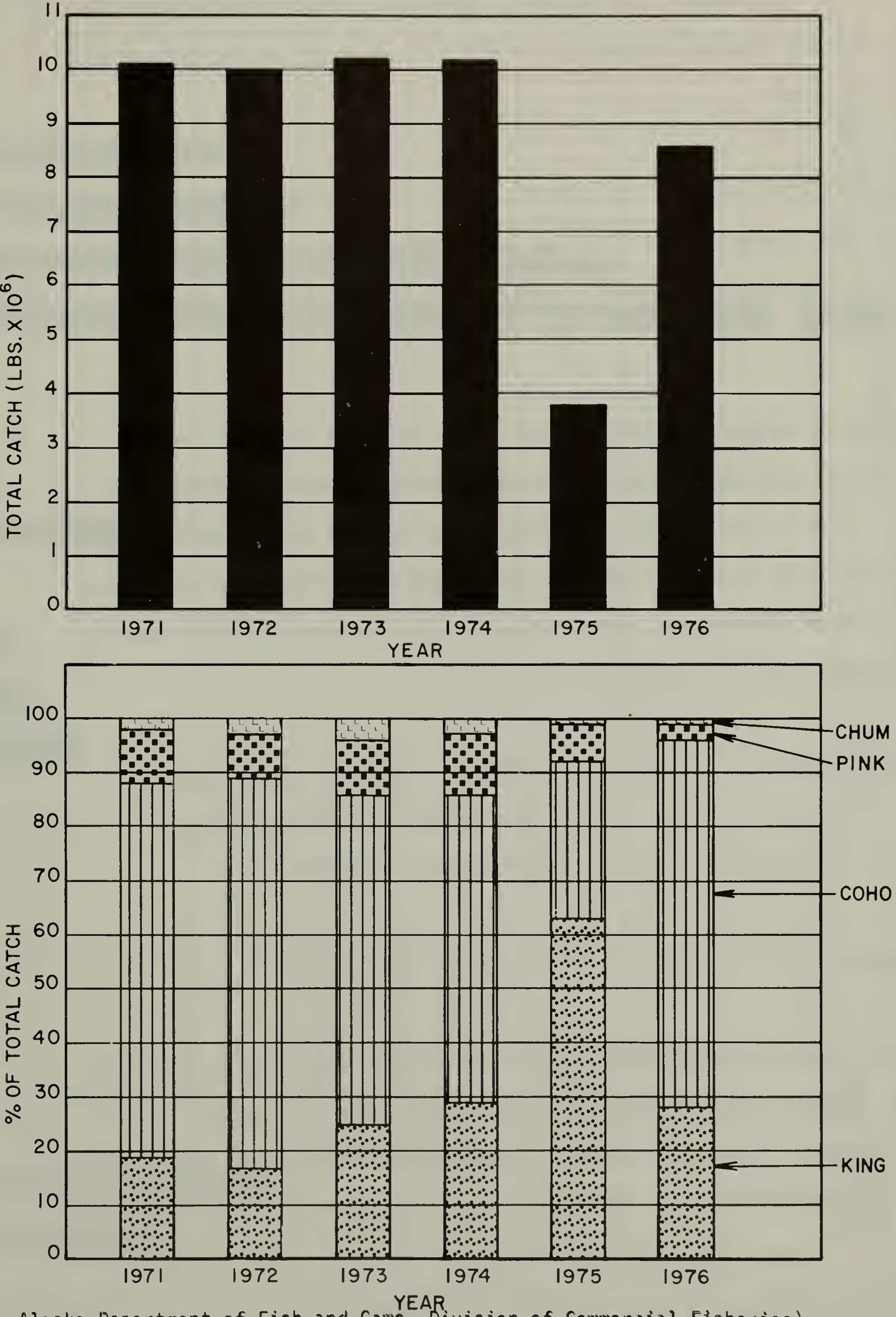
Year	Sub-Area 182	% of southeast Alaska catch	Area 18S-1	Southeast Alaska (Regulatory Area 2)	Total U.S. Catch	Total Catch
1958	1,324	12	1,509	11,198	35,681	64,508
1959	1,574	12	1,873	13,031	40,381	71,204
1960	1,984	16	2,115	12,715	38,058	71,605
1961	1,429	12	1,645	12,286	39,863	69,274
1962	1,145	11	1,384	13,239	40,239	74,862
1963	1,189	12	1,313	10,240	34,139	71,237
1964	1,031	14	1,057	7,434	26,236	59,784
1965	1,773	15	1,929	12,069	30,254	63,176
1966	2,056	17	2,152	12,039	30,114	62,016
1967	1,834	19	2,120	9,409	29,719	55,222
1968	1,181	19	1,205	6,111	19,181	48,594
1969	1,562	17	1,581	9,326	24,763	58,275
1970	1,694	18	1,776	9,367	25,783	54,938
1971	1,284	19	1,311	6,608	21,158	46,654
1972	765	13	908	5,780	20,363	42,884
1973	1,268	21	1,310	5,976	17,290	31,740
1974	922	15	956	5,936	13,938	21,306
1975	1,051	16	1,058	6,545	16,259	27,616
1976	1,034	31	1,058	3,366	13,101	21,868
1977	434		439			

The catch and C.P.U.E. of sub-area 182, as in the rest of Southeast Alaska, has declined over the past 10 years. This decline is attributed to several factors including (1) increased gear effectiveness, (2) a larger proportion of fish being taken by small (less than 5 net tons) and consequently unlicensed vessels; and (3) environmental factors that have contributed to a decline in juvenile halibut abundance (IPHC 1978). There are indications that juvenile halibut stocks are increasing. Because of the poor state of the stock, however, halibut fishing was only allowed during 73 days in 1977 as compared to 123 and 128 days in 1976 and 1975 respectively.

Salmon: All five species of salmon found in Alaska can be caught within lower Glacier Bay, but coho salmon and king salmon usually make up the bulk of the catch.

The total commercial salmon catch in Glacier Bay is not known, as Glacier Bay is part of a large statistical area (A.D.F.&G. area 114) that includes important fishing grounds in Icy Strait and Cross Sound. About 680kg (1500 pounds) of salmon caught in Glacier Bay are sold directly to Glacier Bay Lodge, the rest of the catch is landed at ports outside the Monument. The total salmon catch taken with trolling gear (the only commercial gear used in Glacier Bay) in Area 114 is shown in Figure 37. The catch averaged about 1 million pounds of salmon from 1971 to 1974, then in 1975 showed a precipitous decline. The catch somewhat recovered in 1976. This general pattern may not be accurate for Glacier Bay, as the Bay is probably used more intensively during

Figure 37. SALMON CATCH BY TROLLERS 1971-1976 A.D.F. & G. REGION 114



Source: Alaska Department of Fish and Game, Division of Commercial Fisheries) poor fishing seasons. For example, commercial fishing boat visits to Glacier Bay reached their peak in 1975, the year of the region's poorest salmon catch.

Other Finfish Species: Incidental commercial catches of ling cod (*Ophiodon elongatus*), sablefish (*Anoplopoma fimbria*), and Pacific cod (*Gadus macrocephalus*) occur in ADF&G Area 114 and probably occur in Glacier Bay as well.

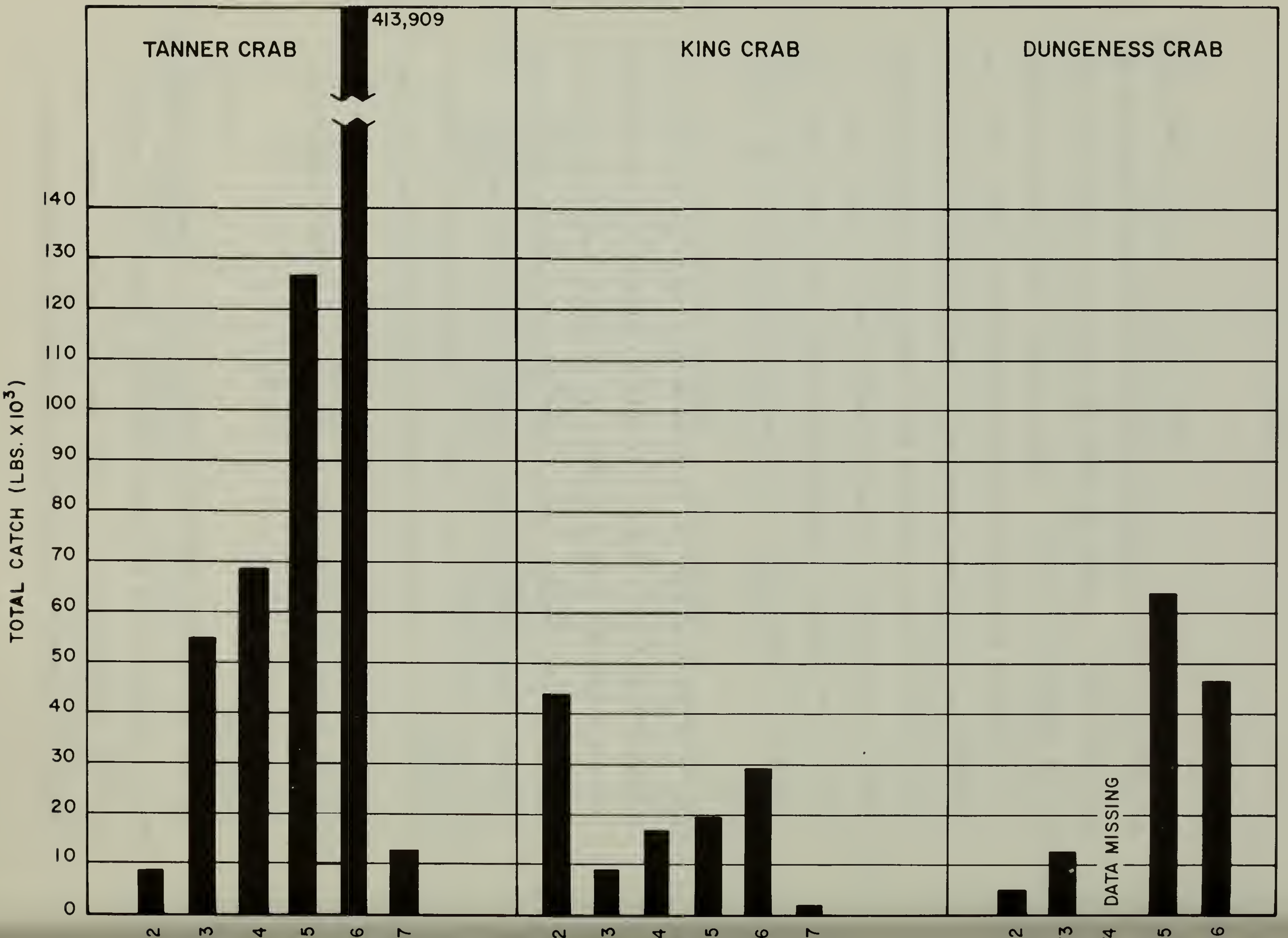
Potential Commercial Finfisheries: It is doubtful that any new fin fisheries will develop in Glacier Bay within the next 10 years. The Bay's capelin and pollock populations (the species most often mentioned for potential fisheries) are not well known but estimates of abundance, recruitment and natural mortality would have to be made before sensible management would be possible.

Capelin, which is not presently fished in Southeast Alaskan waters, is an industrial fish that would be processed into oil and fish meal. This type of processing capability does not exist in Alaska.

Shellfish

Crabs: Tanner (*Chionoecetes bairdi*), blue king (*Paralithodes platypus*) and Dungeness (*Cancer magister*) crabs are all taken commercially within Glacier Bay, with tanner (snow) crabs making up the largest proportion of the catch (Fig. 38). Crabbing activity for tanner and blue king crab

Figure 38. COMMERCIAL CRAB CATCH IN GLACIER BAY (1972-1977)



is largely confined to the winter months while Dungeness crab is taken in the summer. Most of the crab catch is from lower Glacier Bay with occasional contributions from Geike Inlet (see Data Appendix). A large number of Dungeness crabs are taken recreationally and hence are not reported.

Because crab landings are recorded to statistical sub-area by the Alaska Department of Fish and Game, it is possible to assess the proportion of the total Area 114 catch contributed by Glacier Bay. This value varies from year to year (Table 13) but appears to be increasingly significant for all three crab species. From a state-wide perspective, the contribution of southeast Alaska to the State's crabbing industry is minor for king and tanner crabs but of somewhat greater importance for Dungeness crab. For excellent discussions of the biology of and fishery for each of these crabs, see Sections 12, 13, and 14 in Rosenberg (1972).

Shrimp: At present there is no commercial shrimp fishery in Glacier Bay. Exploratory shrimp trawls were conducted throughout much of Glacier Bay in the 1950's (see Data Appendix), and all five species of commercially important pandalid shrimp were found (See Table 14 for a general description of their characteristics). Pink shrimp were by far the most abundant species with significant quantities of sidestripe and coonstripe shrimp also being caught (Ron Holt 1963). Areas within Glacier Bay with high abundances of pink shrimp are shown in Figure 39. Best coonstripe shrimp catches were taken in Charpentier and Geike Inlets and North and South Sandy Coves (U.S. D.O.I., 1967).

Table 13 - Regional Significance of the Glacier Bay Crab Catch

1972-1977

Year	Glacier Bay (lbs)	Region 114 (lbs)	Proportion Region 114 Catch Contributed by Glacier Bay
TANNER CRAB			
1972	9,364	336,805	3%
1973	55,234	574,083	10%
1974	69,224	364,449	19%
1975	127,847	502,966	25%
1976	413,909	688,234	60%
KING CRAB			
1972	44,344	119,855	37%
1973	9,330	100,849	9%
1974	17,348	83,287	21%
1975	19,440	126,225	15%
1976	29,978	68,696	44%
DUNGENESS CRAB			
1972	5,235	105,440	5%
1973	13,373	137,637	10%
1974		146,025	
1975	64,765	161,214	40%
1976	47,162	138,105	34%

Table 14.--General characteristics of the five important species of Alaska shrimp (Barr, 1970).

Species of shrimp	Approximate maximum size	Shrimp per pound	Geographic range in Alaska	Type of gear	Type of bottom	Usual depth of capture	Greatest depth of capture
	Inches	Number				Fathoms	Fathoms
Pink	6-½	60-160	Pribilof Islands-southeastern Alaska	Trawls	Smooth mud	20-100	350
Sidestripe	8-½	20-100	Central Bering Sea-southeastern Alaska	Trawls	Smooth mud	20	350
Humpy	4-3/4	80-180	Bering Strait-southeastern Alaska	Trawls	Smooth mud, sand, organic debris	10-100	100
Coonstripe	8	30-100	Norton Sound-southeastern Alaska	Trawls pots	Smooth mud, sand, rocky areas	25-50	100
Spot	11	6-25	Unalaska-southeastern Alaska	Pots	Rough, rocky	30	266

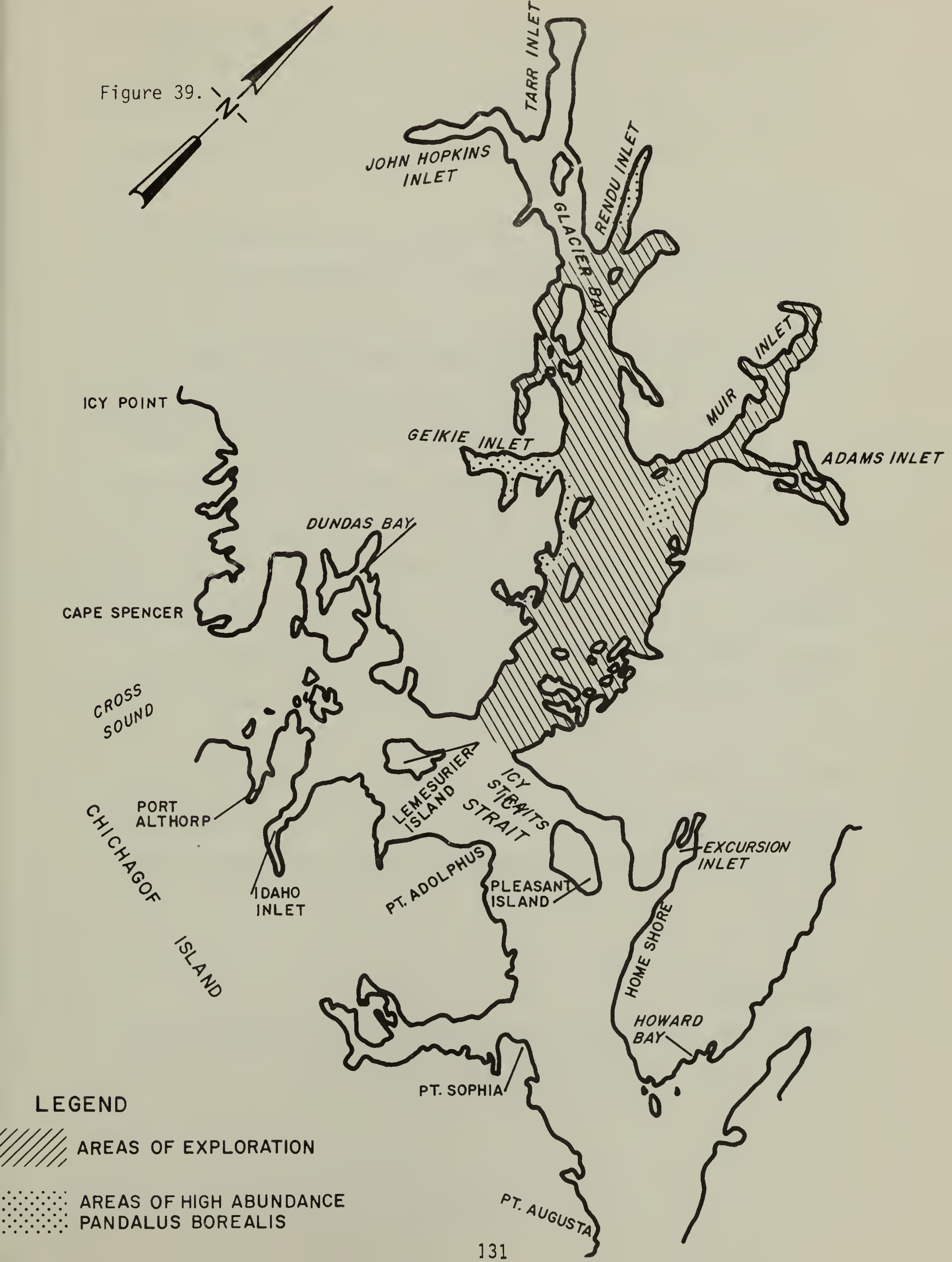


Figure 39.

REAS OF EXPLORATION FOR AND HIGH ABUNDANCE OF PANDALUS BOREALIS
1950-60

Over the years, small scale attempts at commercial shrimp fishing in Glacier Bay have been made; none have been successful. The large distance to a landing port coupled with the relatively low unit prices of pink shrimp make commercial ventures economically marginal.

For more detailed accounts of the pandalid shrimp fishery and shrimp biology, see Barr (1970) and Section 15 in Rosenberg (1972).

Clams: Clamming is a subsistence and recreational, not commercial activity, in Glacier Bay. Although there is no quantitative assessment of either Glacier Bay's clam population or the magnitude of clamming activity, observations by G. Streveler, Glacier Bay Research Biologist, suggest that the more heavily used clamming areas at the mouth of the Bartlett River are becoming over-exploited, at least for cockles (*Clinocardium nuttalli*). The lack of small animals, which would indicate poor recruitment, in addition to probable slow growth rates, is potentially of concern if the clam population continues to experience heavy exploitation.

Paralytic shellfish poisoning occurs in Glacier Bay with the butter clams and mussels being most severely affected. Cockles and steamers are much less affected and consequently receive more intense fishing pressure.

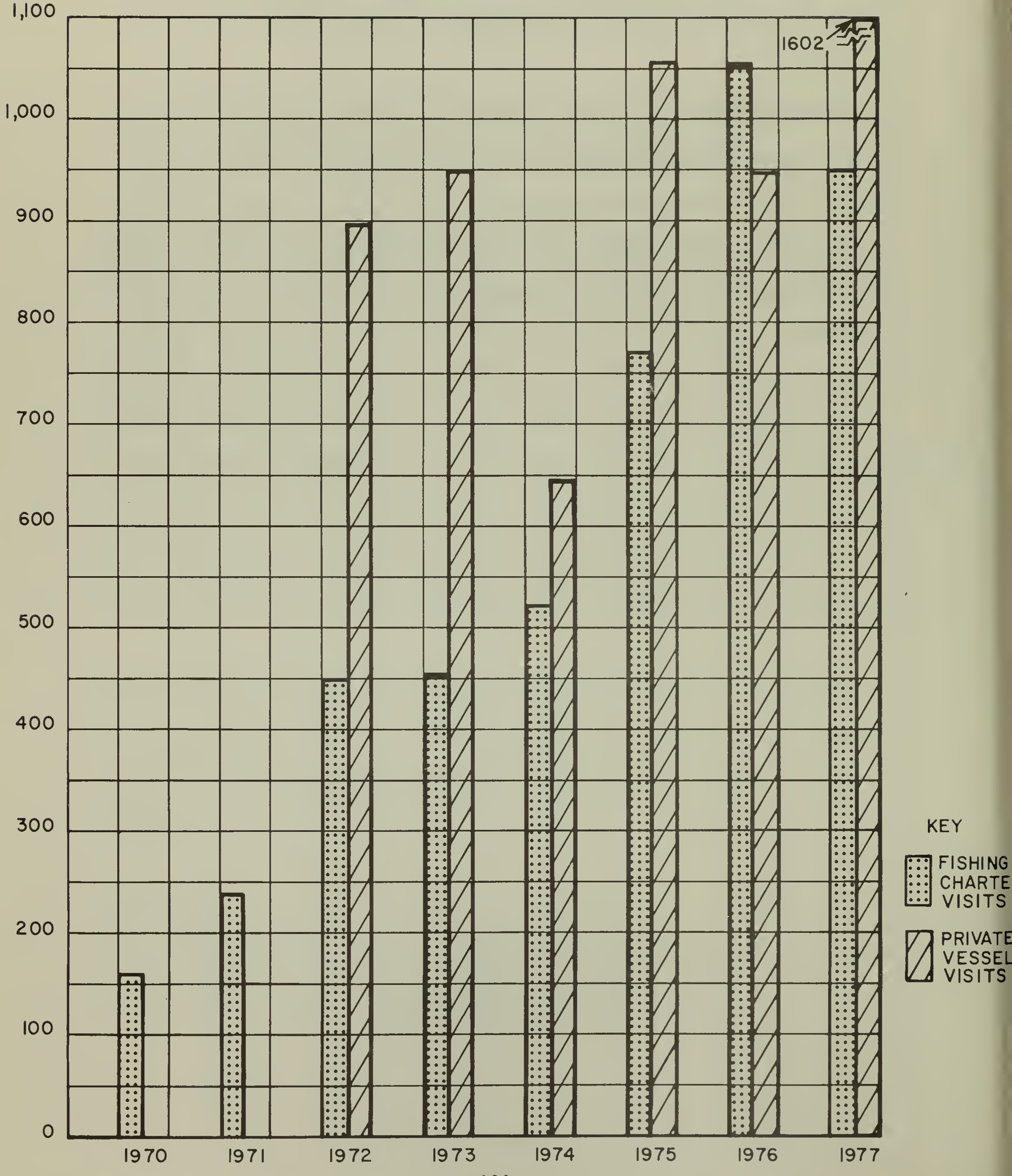
Sportfishing

Sportfishing in Glacier Bay is primarily for salmon (mostly king and coho), halibut, and less importantly, Dungeness crab.

The number of sportfishermen using Glacier Bay has increased dramatically since 1970 (Fig. 40). Incomplete catch records are available for the concessionaire's salmon and halibut catch in 1973 and 1975. More complete catch records are being maintained this year.

To minimize travel time, most concessionaire charter trips fish lower Glacier Bay. The reefs near Point Gustavus, Young Island, and the Marble Islands are preferred halibut areas; salmon fishing is concentrated in Berg and Fingers Bay and along shorelines where kelp beds are found (Chuck Kearns, personal communication).

Figure 40. FISHING CHARTER BOATS AND PRIVATE BOAT VISITS TO GLACIER BAY 1970-1977



VESSEL AND AIRCRAFT TRAFFIC

Almost all visitor use of Glacier Bay National Monument results in some vessel or aircraft traffic in or above the waters of Glacier Bay. Most people who enter Glacier Bay do so on board large cruise ships. For example, in 1977, of the approximately 83,000 visitors to the Monument, close to 75,000, or 90%, viewed the monument from a ship. The majority of the other visitors come to Glacier Bay either in their own boats or take the concessionaire's boat tour when they arrive.

With the exception of large cruise ships, accurate records of the number of boats using Glacier Bay are not kept. However, the trend of increasing vessel traffic is clear from Park Service monthly Public Use Reports (Table 15). More detailed records of vessel and aircraft traffic in Glacier Bay are kept by Charles and Virginia Jurasz as part of their work on whale:vessel interactions. However, their observations only include selected times and locations in the Bay.[1]

Types of Vessels and Aircraft

All types of vessels do not pose the same management concerns. In their whale:vessel interaction work, the Juraszs (1978) categorized vessels into 8 classes and aircraft into 3 classes (Fig. 41).

---

[1] Robert Mattson, University of Alaska, has compiled summer 1977 data. See the Data Appendix for an example of his compilation for June, 1977.

Table 15 - Number of Visits for Different Vessel Types in Glacier Bay, 1970-1977[1]

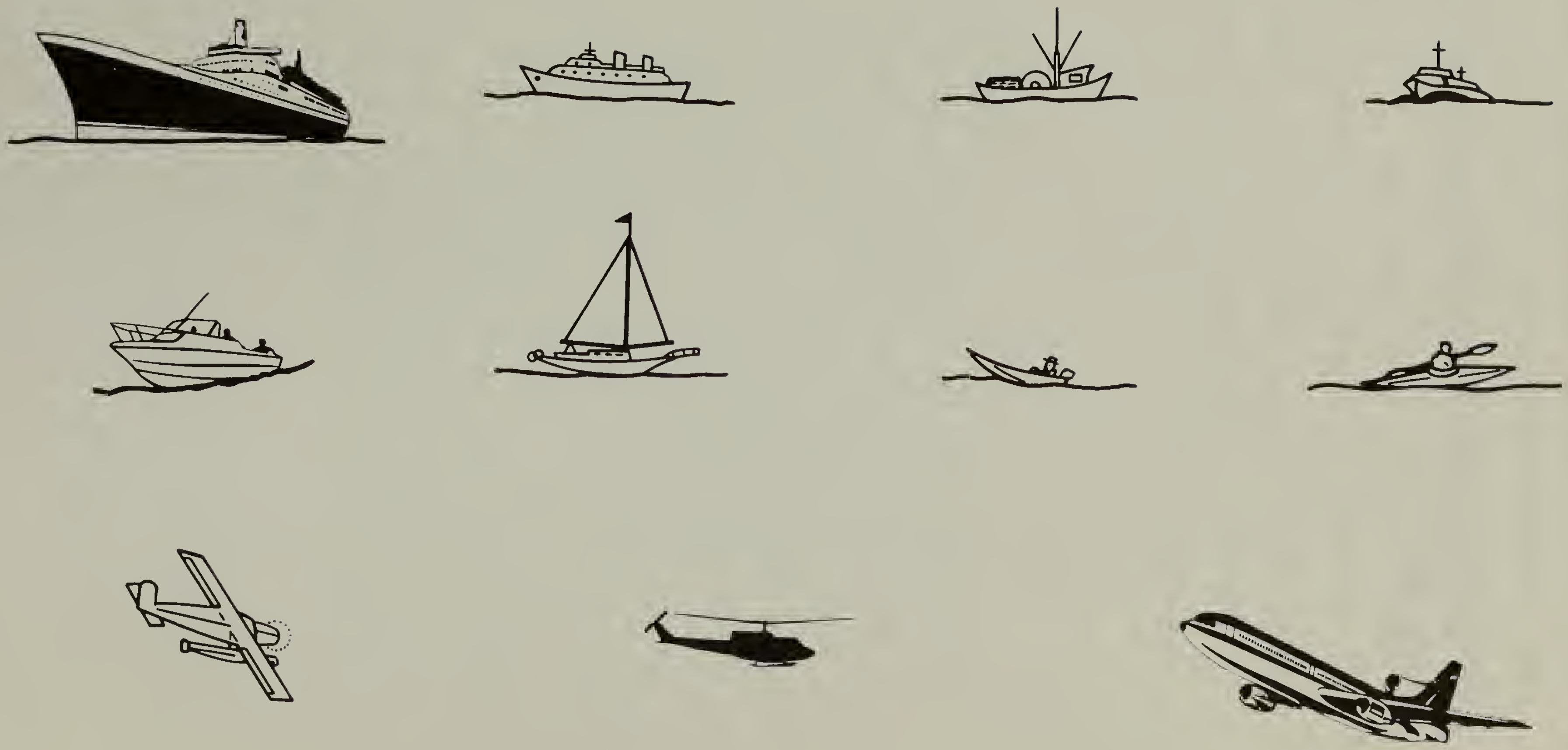
Year	Lodge Tour Boat	Lodge Fishing Charter	Charter/ Private boat	Commercial Fishing vessels	Cruise Ships
1970	2020	160			
1971	2047	237			
1972	3076	456	895	820	
1973	3726	458	945	690	
1974	3398	521	645	550	41,531
1975	4195	772	1058	1647	42,479
1976	6546	1056	947	1312	46,488
1977	6702	949	1602	1045	77,870

Number of Cruise Ships in Glacier Bay, 1973-1978[2]

1973	1974	1975	1976	1977	1978
43	57	93	123	142	122

[1] Data compiled from NPS Form 10-157, Monthly Public Use Reports.
[2] Data supplied by Bruce Paige, Glacier Bay National Park Chief Naturalist.

Figure 41. A CLASSIFICATION OF VESSELS AND AIRCRAFT BASED ON CRAFT SIZE. (FROM JURASZ AND JURASZ, 1978).



The definition of their vessel and aircraft classes are based on vessel size, hull design (often relates to speed), engine drive and train characteristics (relates to noise), and the vessel's activity when in Glacier Bay.

SEWAGE INPUT

The four major water pollution problems associated with human waste are 1) hazards to human health, 2) oxygen reduction in the water column, 3) eutrophication from dissolved organic and inorganic substances and 4) aesthetic offences. Because of the very small amount of sewage being discharged into Glacier Bay and the well mixed nature of the water in the lower Bay, probably none of the above mentioned problems are now significant.

Sources of Sewage to Glacier Bay

A small (21,000 gallons per day (GPD) capacity) sewage treatment plant that uses primary plus secondary treatment discharges effluent into Glacier Bay from May through September. Secondary sewage treatment plants are effective in reducing most of the biochemical oxygen demand (90%), chemical oxygen demand (80%) and suspended solids (90%) of the incoming effluent. They are less effective in removing nitrogen (50%), phosphorus (30%) and dissolved minerals (5%). The plant processes the sewage from the Glacier Bay Lodge and Bartlett Cove. The six inch diameter outfall empties into about 3.8m of water just south of the dock in Bartlett Cove. The amount of effluent discharged occasionally reaches the plant's capacity and averages about 16,000 GPD during the period the Lodge is in full operation.

The other National Park Service buildings discharge their effluent into a septic system located shoreward of the lagoon in front of Park Headquarters. The impact of the septic system on the poorly flushed lagoon is not known. Another potential source of sewage to Glacier Bay is discharges from the many small vessels using the Bay. From a perspective of total sewage input to the system, this latter source is probably not significant.

MINING

The Mining in the Parks Act (P.L. 94-429), which closed all NPS units to mineral entry, was signed by the President on September 28, 1976. The Act directed the Secretary of Interior to formulate regulations governing mining on park lands, to determine the validity of any unpatented mining claims, and to evaluate the environmental consequences of mineral extraction from these lands. The mining regulations (CFR 35 Part 9, Subpart A) prepared as a result of P.L. 94-429 were promulgated on January 26, 1977. Included in the regulations are provisions calling for proper recordation of unpatented mining claims with the Secretary of Interior, preparation of a plan of operations for any activities conducted within the park and filing of a performance bond in an amount equal to the estimated cost of reclamation. As a result of P.L. 94-429, the National Park Service prepared a report entitled "Environmental Consequences of Mineral Extraction: Glacier Bay National Monument and Mount McKinley National Park and Discussion of Alternatives for Acquisition of Mining Claims and/or Boundary Modifications to Reduce Possible Acquisition Costs: Glacier Bay National Monument" (February 1979). The reader is referred to this report for a detailed evaluation of the mineral situation in Glacier Bay; copies of the report are on file at the monument headquarters in Juneau, at the monument library and at the Pacific Northwest Regional Office in Seattle, Washington. Information in this section is abstracted from that report.

One patented claim group (NUNATAK LODE) and one valid unpatented claim (LEROY NO. 1 AMENDED) are located within Glacier Bay National Monument. Only the LEROY NO. 1 AMENDED claim is located within the water and viewsheds of Glacier Bay.

LEROY NO. 1, AMENDED is located at Mt. Parker (between Reid and Lampugh Glaciers) and totals 20 acres. The claim was located by the present owner's grandfather (Albert L. Parker) and was mined from 1938 to 1950. During those years, 4,572 ounces of gold and 1,628 ounces of silver were taken from this claim. The Leroy gold claim, with its abundant but disseminated veinlets of gold, would not be profitable for a large-scale mining venture but could support a small, low overhead hand-mining operation. Mining would probably be by the resueing method and would be accomplished by four men in two seasons (8 months). It would be a hand-labor operation carried out entirely underground. Additional work underground would include sinking a 60 foot vertical shaft and driving 50 feet of drifts. This work would develop 600 tons of ore which would be stockpiled in bags and barged out at the end of the second season. Assays show this ore may contain up to 505 oz. of gold and 176 oz. of silver. No milling would be done within the monument and no additional above-ground structures would be constructed. Supplies needed for mining this deposit would be airlifted by helicopter to the adit sites since no road exists. Power, water and sanitary disposal would be provided on a temporary basis; no permanent utilities would be installed.

SECTION IV

ANALYSES AND CONCLUSIONS

ANALYSES AND CONCLUSIONS

Introduction

The discussions in Sections I and II have emphasized that there is little information available on the Glacier Bay marine ecosystem, and because of its uniqueness, knowledge gained from studies conducted in other fjords if often not directly transferable. Using the submodels presented in this report, as a base, the first part of this section attempts to summarize studies needed to provide a better basic understanding of the Glacier Bay biological system. An analysis of the potential impacts of major human activities on both the Glacier Bay ecosystem and on the visitor's experience of that system follows. We then attempt to look at critical interrelationships or components of the Bay system that have a direct bearing on management issues, and discuss future research directions needed to address these issues and facilitate decision making.

Biological Research Needs

Glacier Bay is unique, primarily because of its dramatic deglaciation, but also because of its long period of protection and consequently lack of development under the administration of the National Park Service. Both of these attributes makes Glacier Bay an ideal site for biological research. The rapid deglaciation provides a tremendous opportunity for studying the sucession of marine plant and animal communities which has occurred within a relatively small temporal and geographic framework. Such studies would parallel the classic terrestrial plant succession studies carried out in the monument by W.S. Cooper. As with the terrestrial environment, Glacier Bay's marine communities range from well-developed complexes in the lower Bay to relatively simple food chains in the waters of the upper inlets.

Because so little is actually known about Glacier Bay, the information required to first describe and understand the various biological components tends to be very basic. A list of studies specific to each of the trophic levels follows. These studies are oriented to the gathering of basic data and are therefore separated from those studies oriented to specific management or systems problems which are discussed later in this section. The listing of needed studies that follows is not assigned priorities as it is beyond the scope of this paper to do so. It is the authors' recommendation that research priorities can best be developed through a workshop which convenes marine scientists and managers familiar with Glacier Bay and uses this document as a base. The goal of such a workshop would be to review the available data and models summarized in this report and to design and prioritize appropriate data gathering studies necessary to meet the needs raised here.

Phytoplankton and Macroalgae Studies

The plant submodel examined a generalized grouping of phytoplankton and macroalgae in general. Because of the lack of data, no attempt was made to examine the factors influencing the growth, death, and importance of individual species. Basic descriptive work on the species composition and productivity of both groups over annual cycles in representative habitats of Glacier Bay is a starting point to furthering our understanding of this system component. The utilization of the Bay's primary production by consumers, the proportion contributed to detritus, and the contribution of the different producer species in the food web is likewise a needed area of study. The influence of suspended sediments in the Bay on the primary productivity of both components was illustrated in a generalized manner in the submodel, and appears to be an important control on productivity. Again, this supposition needs quantification. Additionally, different species react differently to this factor, and the potential interaction between the time of peak plant productivity and the pulse of sediment into the Bay should be examined.

Zooplankton Studies

The zooplankton submodel presented a view of the population dynamics of the three groupings of zooplankton integrated over the growing season. (Time was implicit in the submodel). In actuality, the abundance of the various species of zooplankton varies considerably over time, and is strongly influenced by physical factors such as temperature and salinity as well as the availability of phytoplankton. Zooplankton abundance and composition in turn affects species dependent on zooplankton for food, and may therefore affect the behavior and use of Glacier Bay by migrant species of birds, fish and whales. Many of these zooplankton feeders are species which have a high visitor interest, e.g., humpback whales. A starting point then is a basic description of Glacier Bay's zooplankton populations over an annual cycle, and a complementary study of zooplankton predation.

Benthic Studies

Little is known about the composition and abundance of the benthic populations in Glacier Bay, and this is a logical starting point in the study of this component of the marine ecosystem. The benthic submodel is again a generalized one. However, certain species such as shrimp, clams, and crabs, are of particular importance, and separate studies describing their role in the system are needed. Shrimp and crabs appear to be a key food resource for a host of other animals, and crabs and clams are presently under pressure from human predation. The importance of organic matter brought in on the bottom as a food source for shrimp and other epifauna is not known, but may be significant and should be studied.

The infauna of the subtidal benthic communities is not well known and offers excellent opportunities for studying successional changes in a subtidal marine environment. They also could be used to study the structure and functioning of a community that is naturally stressed by high sedimentation rates. The influence of sedimentation rates and other related physical factors was shown in the benthos submodel, however, based on present knowledge, quantification of these factors is not possible.

Fish Studies

As with the other trophic levels, the first point of study of the fish populations should be concerned with determining the composition and abundance of the finfish populations over an annual cycle in representative habitats in Glacier Bay. Determination of spawning areas needs to be made. It is that likely as the glacial recession continues, additional spawning areas will be made available and fish populations will continue to expand into the upper reaches of the Bay. These processes should be monitored.

The fish submodel presents an integrated picture of the major categories of fish in a "homogeneous" Glacier Bay. In actuality, the different species occupy discreet areas of the Bay which may change throughout the year and, in many instances spend only part of the year in the Bay. Where Glacier Bay's fish, especially commercially important fish, go when they leave the Bay has management implications that will be discussed below. From a biological perspective this differential use affects the food webs of those species that are either dependent on fish for food or are prey items for fish.

Mammal Studies

While the distribution of seals and humpback whales has been carefully monitored in Glacier Bay, very little attention has been given to killer whale and harbor porpoise populations. A study of the latter species, which seems to be relatively abundant in the Bay, is needed. Work on the feeding habits of all of the Bay's marine mammals, especially whales and seals is necessary to determine why these animals seem to prefer certain regions within the Bay, and if food availability controls population numbers. Additionally, the winter location and activities of Glacier Bay's whale and much of its seal population must be examined.

Bird Studies

As was indicated in the discussion of the bird submodel, because of many years of observation, bird species, numbers, and locations are relatively well known and documented for Glacier Bay. Much less is known about bird feeding habits or their effects on the marine ecosystem. This type of knowledge is essential to tie the bird submodel to the rest of the marine ecosystem. Such data is needed for nesters as well as migrant and winter residents. Environmental factors influencing migrant stopovers in the Bay are not clear, but may be food, favorable location on the flyway, calm waters, or the relative security offered by the monument's lack of development. These factors need to be assessed.

Finfishing

The impacts of fishing for salmon and halibut in Glacier Bay are illustrated by an overlay on the combined Glacier Bay ecological submodels in Figure 42. As can be seen, harvest of these species shows some reverberations through the system; however the major impacts of commercial fishing are probably species specific.

As illustrated in Figure 42, halibut and the several species of salmon function as predators in the system, feeding on other finfish and benthic organisms. They also serve as food sources for some birds, fish and marine mammals (in the case of spawning salmon, terrestrial mammals as well). Juvenile salmon (included in the small pelagic fish component) are especially important prey items. While it is unlikely that commercial fishing of any of these species would reduce them to a point of extinction in the Bay, they could be reduced to a point where neither commercial nor sport fishing is no longer rewarding.

- - - - CRABBING
——— FIN FISHING

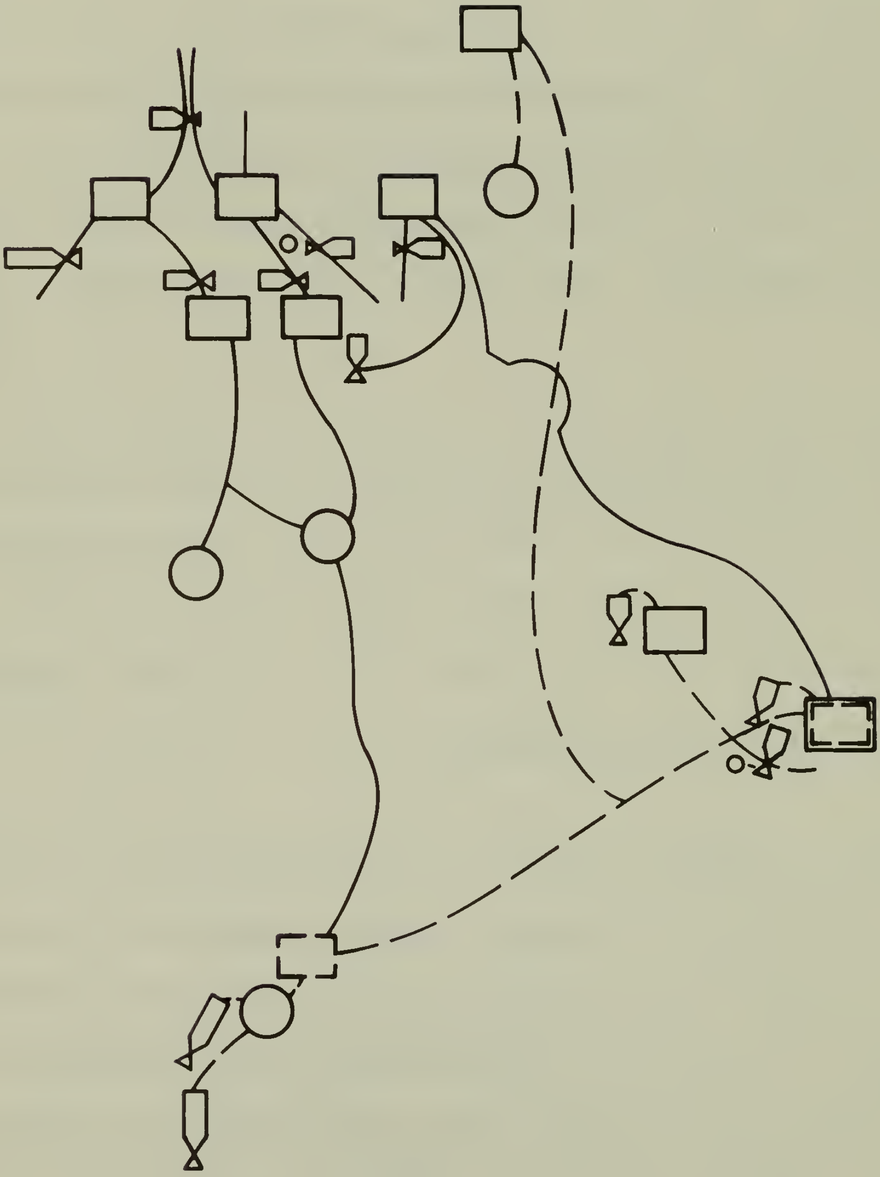
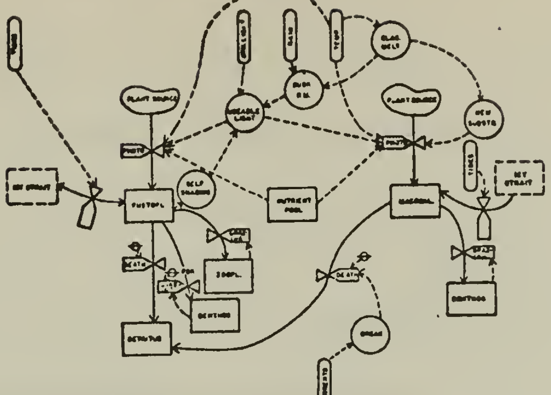
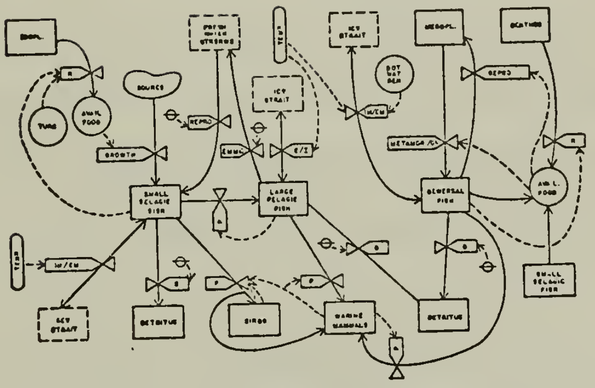


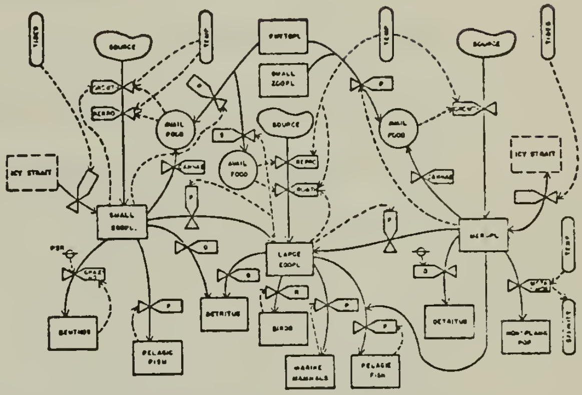
FIGURE 42. IMPACT OF FIN FISHING AND CRABBING ON THE BIOLOGICAL SYSTEM OF GLACIER BAY



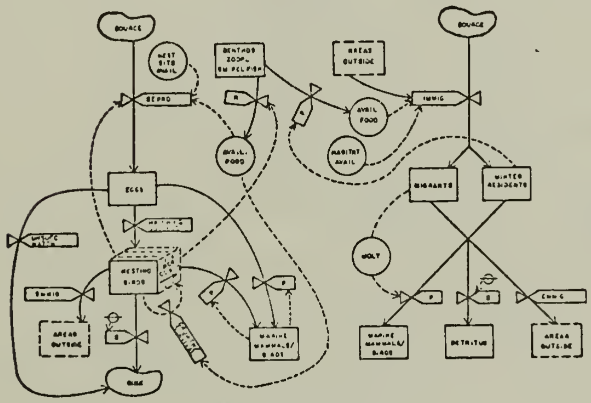
LACIER BAY ECOLOGICAL MODEL
PLANT SUBMODEL



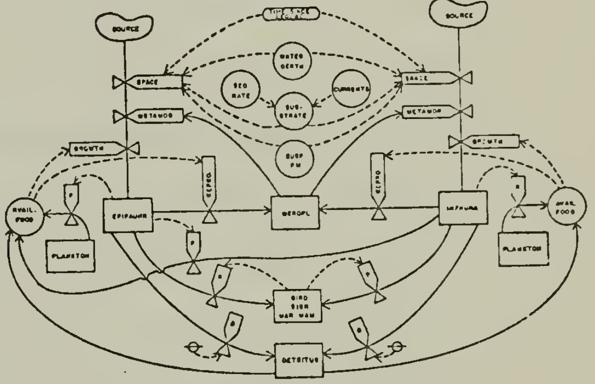
GLACIER BAY ECOLOGICAL MODEL
FISH SUBMODEL



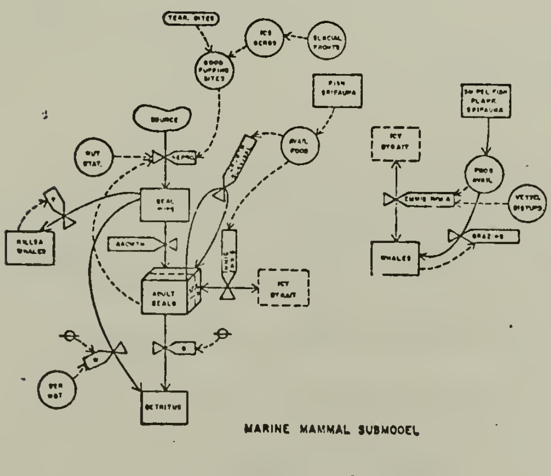
GLACIER BAY ECOLOGICAL MODEL
ZOOPLANKTON SUBMODEL



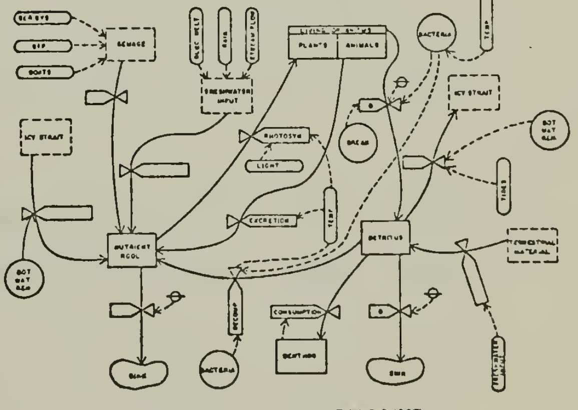
GLACIER BAY ECOLOGICAL MODEL
BIRD SUBMODEL



GLACIER BAY ECOLOGICAL MODEL
BENTHOS SUBMODEL



MARINE MAMMAL SUBMODEL



DETRITUS/NUTRIENT REGENERATION SUBMODEL

Sport fishing for salmon and halibut are major parts of the experience for selected visitors who charter concessionaire craft or arrive in their own boats. Diminishment of this part of the visitor experience would be significant as is illustrated by the overlay on the visitor experience model showed in Figure 43. While the potential exists for salmon or halibut to be replaced by ecological equivilents in the context of their role in the biological system, it is unlikely that any equivalent would replace them in terms of the visitor's sportfishing experience. The importance of sampling commercially caught "Glacier Bay Seafood" at the lodge is also of some importance to the visitor.

Halibut: The life cycle of halibut was illustrated in Figure 26. The periods of residency of halibut in Glacier Bay are not known but migration in and out of the Bay is likely. Most halibut reproduce offshore and consequently a spawning activity in Glacier Bay is probably minimal. However, both halibut reproduction and migration are subjects that require research attention in Glacier Bay. Since halibut appear to use the Bay in a transient manner, fishing pressure both within and outside Glacier Bay affects the population. Coordinated research efforts with the International Pacific Halibut Commission will be necessary to adequately examine this important species.

Salmon: All species of salmon except king are seasonal inhabitants of Glacier Bay. Adult salmon enter the Bay in spring. Young salmon leave the fresh waters where they are born and migrate through the Bay to the ocean. The time the juveniles of each species spends in the Bay varies (see Table 7). Better estimates of salmon escapement to Glacier Bay are

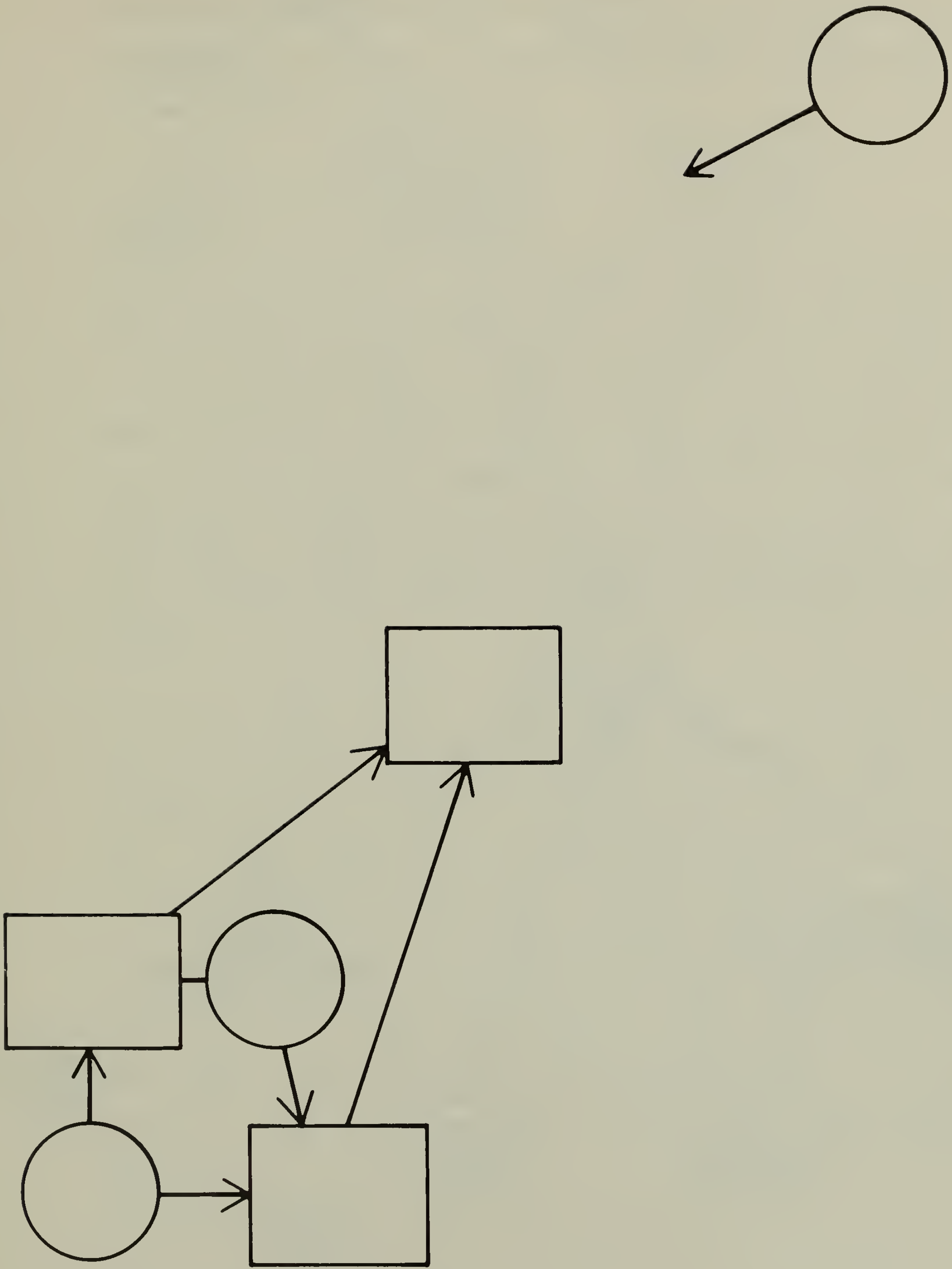
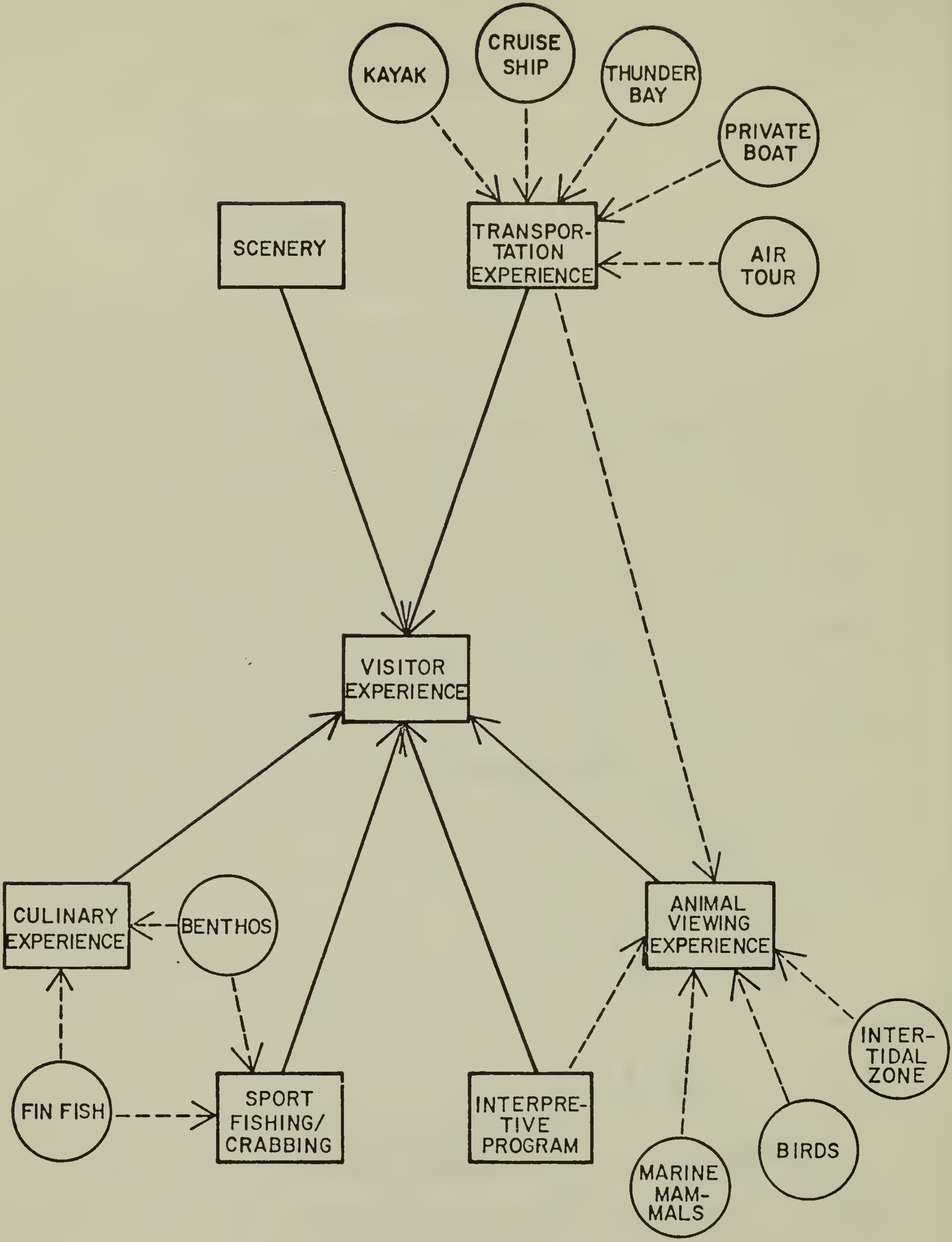


FIGURE 43. IMPACT OF COMMERCIAL FISHING AND CRABBING ON THE VISITOR EXPERIENCE



VISITOR EXPERIENCE SUBMODEL

needed to adequately assess the population. Additionally, the colonization of feeder streams to Glacier Bay by salmon as deglaciation continues must be monitored.

Crabbing

Crabbing, like commercial fishing, appears to mainly affect the population dynamics of the harvested species and to have only a minor impacts on other system components. Effects of harvesting crab in the Bay was shown in Figure 42. Impacts include a slight reduction in the total food supplies available to mammalian, fish and bird predators. Should crab numbers in the Bay be reduced by commercial exploitation, their role in the Bay, would probably be taken by an ecologically equivalent species.

Crabbing provides an element of the visitor experience through the consumption of fresh, commercially caught crabs at the Glacier Bay Lodge. Sport crabbing effort is focused on Dungeness crab. Since these animals only inhabit sandy shores, a relatively scarce habitat in Glacier Bay, population could become depleted in certain habitats if fishing pressure increased. The impact of diminished Dungeness crab populations in the Bay on the visitor experience was also shown in Figure 43. More accurate records of crab harvests and populations are needed to assess this situation.

Vessel and Aircraft Traffic

The use of vessels and aircraft in Glacier Bay has created significant management concerns in the Monument. Planning studies on Glacier Bay

National Monument advocate the use of air and water transportation because they require no permanent facilities, create seemingly little impact and provide an excellent opportunity for the visitor to experience the resource at close hand. The result of this policy is that almost all of Glacier Bay is in a wilderness condition. There are, in fact, only five miles of road in the Monument. However, in recent years, the large amounts of vessel and aircraft traffic have created several management problems. The elements of the natural system impacted by vessel traffic are illustrated in Figure 44.

Vessel and Aircraft/Wildlife Interactions: Based on their observations over the last three years, Charles and Virginia Jurasz feel that there is a strong indication of disturbance of Glacier Bay's humpback whale population by certain classes of vessels. The large cruise ships (Vessel Classes 1 and 2) and high RPM charter and touring vessels (Vessel Class 4) appear to evoke the most stressful responses from the whales. During the summer of 1978, data were collected on the displacement of whales from Glacier Bay because of vessel traffic. The National Park Service is currently completing an environmental assessment of several vessel management schemes which attempt to reduce negative vessel/whale interactions.

Glacier Bay's harbor seal population is also affected by vessel and aircraft traffic. Streveler (1978) expresses concern that aircraft (especially helicopter) and vessel traffic in the upper Bay pupping grounds cause mother and pup to hastily leave an iceberg. This can lead to the separation of mother and pup and consequently starvation of the pup.

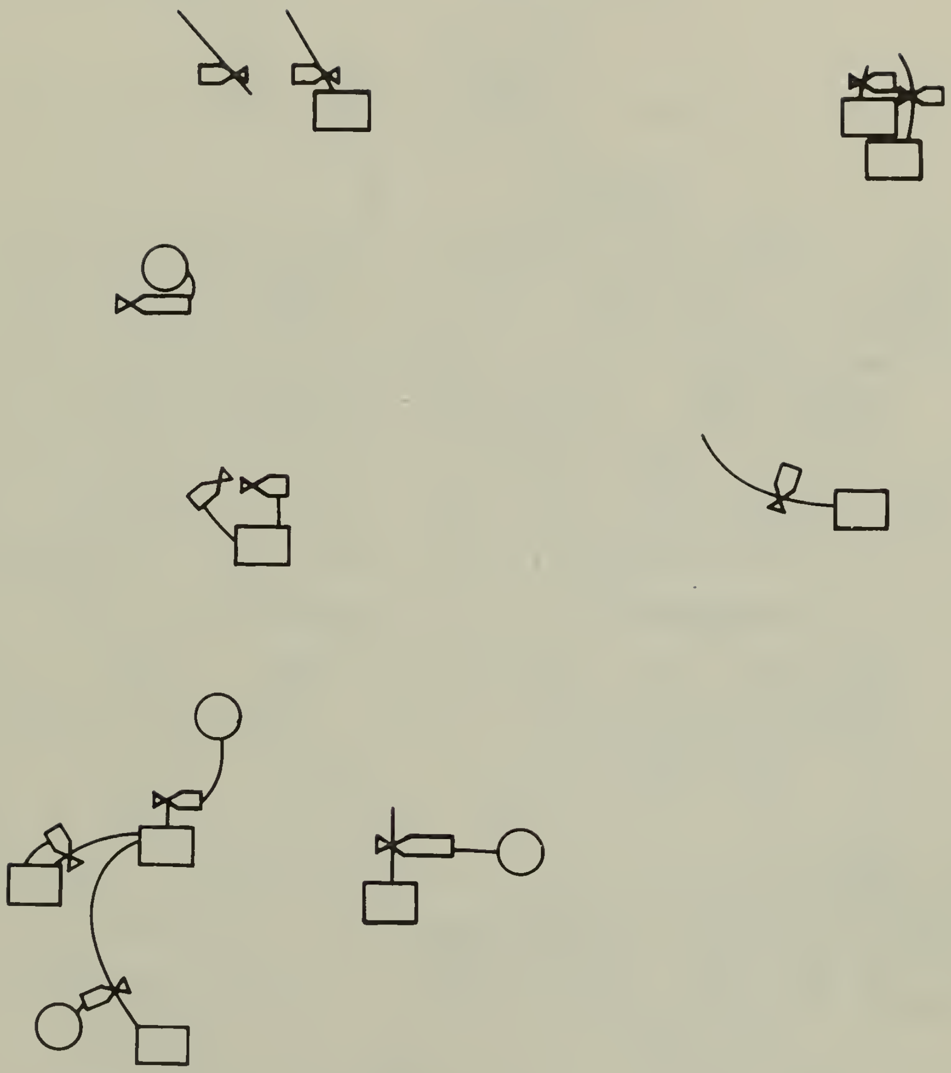
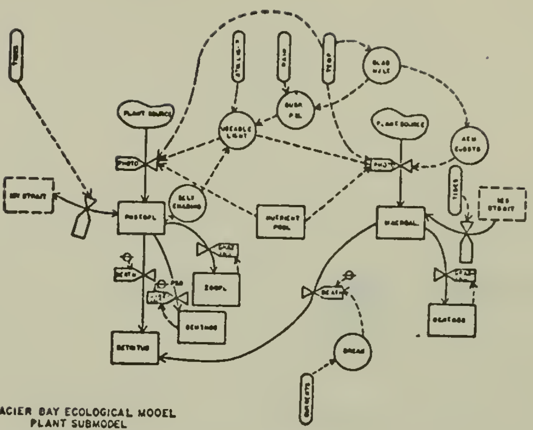
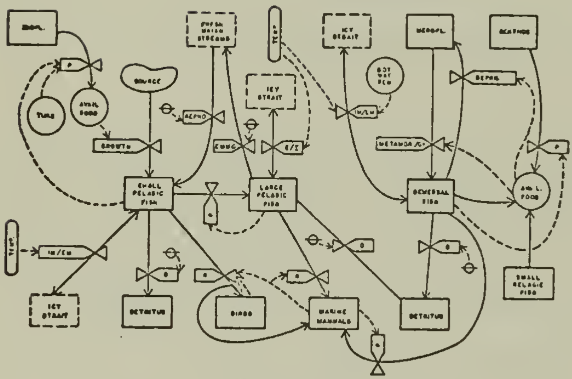


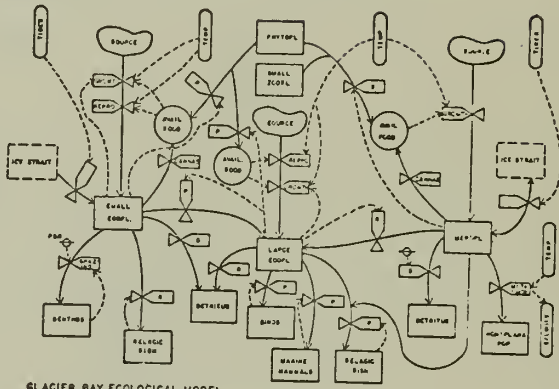
FIGURE 44. IMPACT OF VESSEL TRAFFIC ON THE BIOLOGICAL SYSTEM OF GLACIER BAY



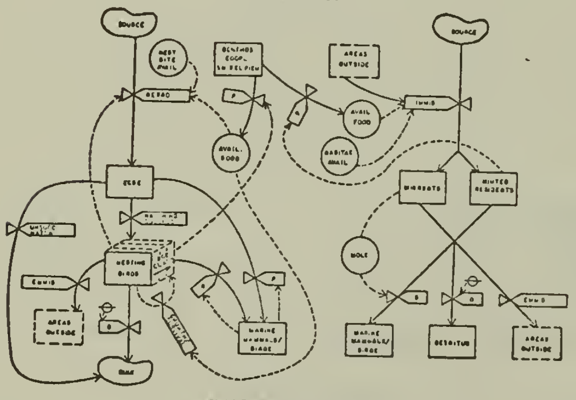
LACIER BAY ECOLOGICAL MODEL
PLANT SUBMODEL



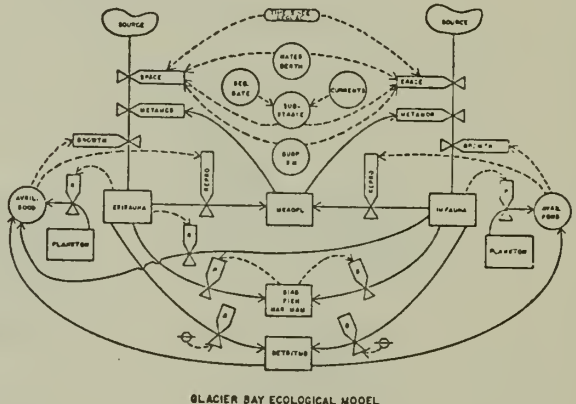
GLACIER BAY ECOLOGICAL MODEL
FISH SUBMODEL



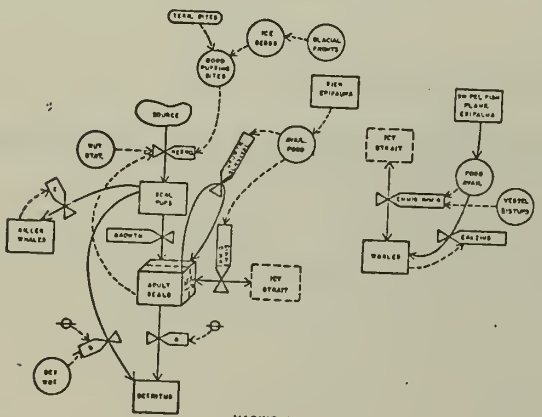
GLACIER BAY ECOLOGICAL MODEL
ZOOPLANKTON SUBMODEL



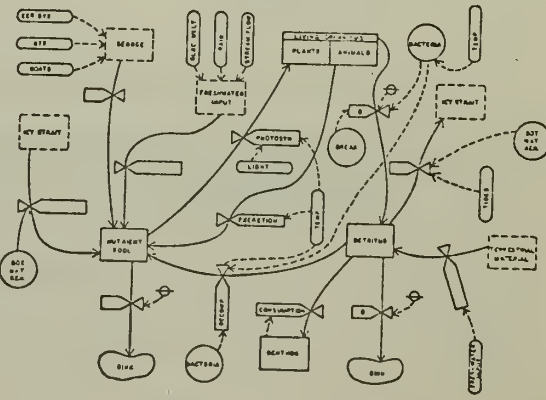
GLACIER BAY ECOLOGICAL MODEL
BIRD SUBMODEL



GLACIER BAY ECOLOGICAL MODEL
BENTHOS SUBMODEL



MARINE MAMMAL SUBMODEL



DETRITUS / NUTRIENT REGENERATION SUBMODEL

Impacts of vessel traffic on bird populations have not been studied in Glacier Bay. A study of vessel/sea bird interactions in Kenai Fjords will be undertaken during the summer of 1979 by Dr. Edward Murphy, University of Alaska. This study should also shed light on the situation in Glacier Bay.

The wildlife species which appear to be most adversely affected by vessel and aircraft traffic are, as is illustrated in the overlay of the visitor experience model shown in Figure 45, those which contribute most significantly to the visitor experience. What seems to be developing is a "Catch-22" situation where the method of observation is the vehicle which disturbs the animals observed, making them less visible.

Noise: Most vessels are noisy, both above and under the water. The Juraszs suspect that auditory stimuli are the major elicitors of stress responses in whales. The above water noise is also of management concern in so far as it detracts from the wilderness nature of Glacier Bay.

Air Pollution: Stack emissions from cruise ships have been observed to accumulate as extensive, visible haze layers above Glacier Bay, especially during clear, calm weather. Benson et al. (1977, 1978) have shown that Glacier Bay, especially Muir Inlet has a very low tolerance for air pollution because of the frequent temperature inversions that occur over Glacier Bay and the exceptionally slow, nearly unidirectional winds in the lowest air layer (during the summer). A more detailed analysis of pollutants trapped in the atmosphere above Glacier Bay is now needed.

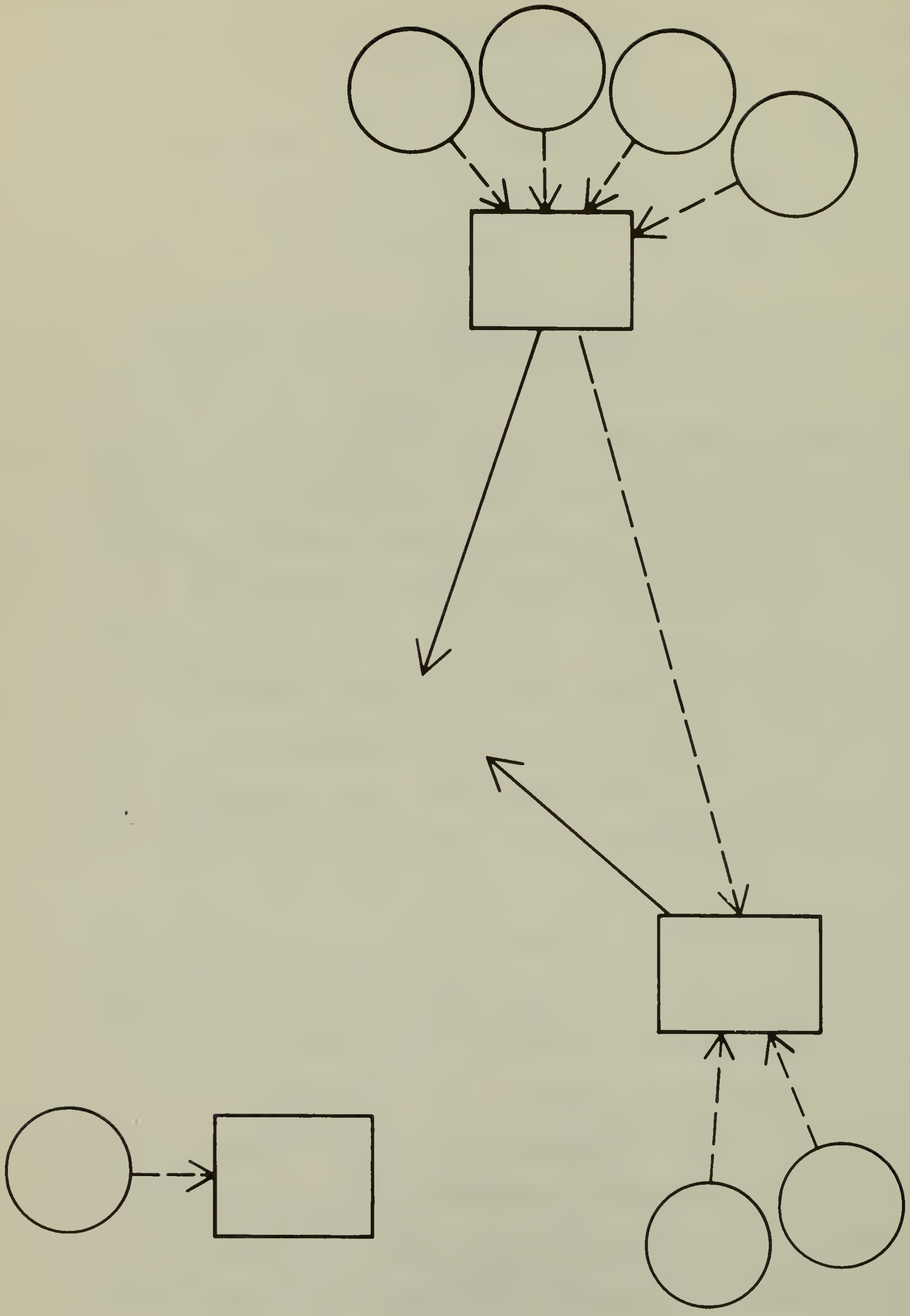
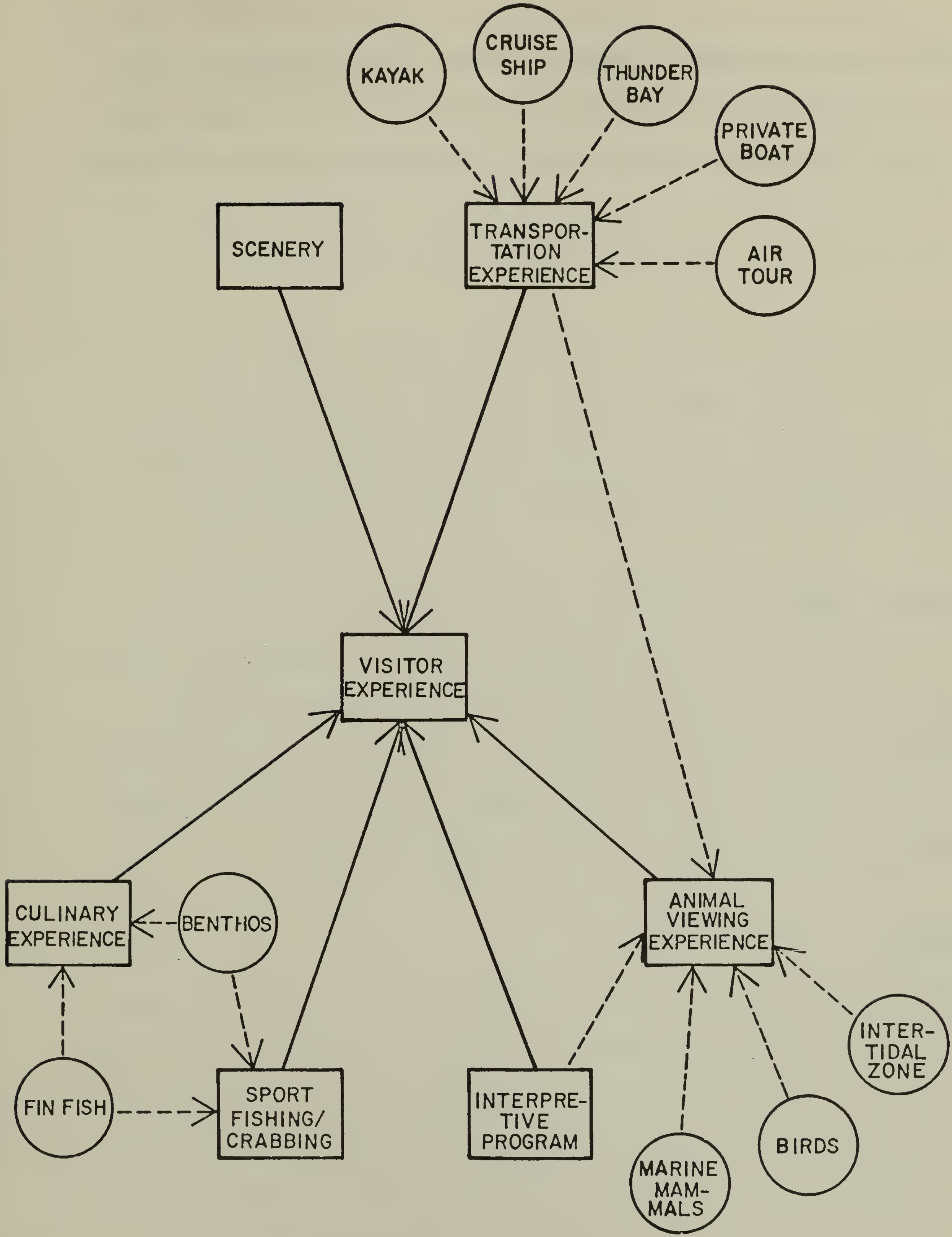


FIGURE 45. IMPACT OF VESSEL TRAFFIC ON THE VISITOR EXPERIENCE



VISITOR EXPERIENCE SUBMODEL

Hydrocarbon Discharges: Limited discharges of hydrocarbons occur in Glacier Bay through fuel spillages at Bartlett Cove and engine exhaust. The quantities released and settling into the sediments are probably too small to be detected. The only area where elevated levels might possibly occur is in the vicinity of the dock in Bartlett Cove.

Sewage Discharge: The U.S. Coast Guard regulates sewage discharges from vessels on coastal waters. A copy of their regulations is included in the data appendix. At the present time it is doubtful that effluent entering Glacier Bay from vessels is of ecological significance.

Sewage Disposal: The present level of sewage input to Glacier Bay is very low and does not raise any major ecological or management concerns, except possibly in the case of the septic system/lagoon discharge. Future issues which may later need to be addressed and analysed include: 1) the consequences of introducing sewage to any of the small tributary inlets in the upper Bay; and 2) the disposal of sludge.

Mining

Impacts on the Glacier Bay marine system from the exploitation of the LEROY NO. 1, AMENDED claim would be minimal. Helicopter support for the miners might coincide with the seal pupping activity in Johns Hopkins Inlet (see Vessel and Aircraft Traffic section) but even this could be avoided by planning. Of greater management concern is that the mining operation would be clearly visible to the approximately 80 percent of monument visitors that go directly past the claim site aboard cruise ships. The impact of seeing the claim on their overall experience of their visit to Glacier Bay cannot be quantified. Backcountry use in the Mount Parker area is increasing. Mining in the area could adversely affect the wilderness experience sought by hikers, campers, and kayakers.

SUMMARY

This project has attempted to use the precepts of systems modelling and analysis to create a framework, in the form of conceptual models, to analyze and provide a better understanding of the marine ecosystem of Glacier Bay. We have tried to maintain a format that makes the report a useful data source for marine scientists, a research guide for resource specialists, and a concise, readable overview for park managers. In attempting this, we have learned a great deal, both about the methods we have used, and about the marine system of Glacier Bay.

The objectives of this project were stated in the introduction. Because there are so little data available on almost all facets of the Bay, it was difficult to precisely delineate the most significant ecological components. Conceptual models are at a disadvantage in this respect. Significance, in terms of the role played in the system, e.g., in energy flow or nutrient cycling, is best determined quantitatively. Likewise, we have found that conceptual models are at a disadvantage in looking at the proposed pathways of potential impacts on the system. Many of the potential impacts probably involve small changes such as shifts in species composition or abundance. Since our models lump species, and are not quantitative, such impacts are difficult either to discern and illustrate.

At the same time, we found that our approach provides a clear overview of the important components of the system, unburdened by the greater detail that would be involved in a quantitative approach. This is a distinct advantage given the diversity of our audience. A quantitative model would be difficult to develop, and because so many species play a minor role in the functioning of the system, it would in the long-run suffer from the same deficiencies as the conceptual approach.

The conceptual submodels and associated overlays have gone through several drafts and refinements in the production of this report. One factor which emerged in this process was that those components of the marine ecosystem which seemed to be impacted most by existing and potential activities in the Bay are species which appear to play a minor role in the system's energy flow and nutrient cycles. These same species, however, play a major role in the visitor experience. It is this contrast we hoped to illustrate in comparisons of the visitor experience model with the various biological submodels.

The role that the potentially impacted species play in the experience of a visitor at Glacier Bay has been discussed and their importance in this regard needs no further emphasis. Glacier Bay quite simply would not be the same without humpback whales, seals, or halibut.

The control or stability that the marine mammals, birds, commercially harvested fish, and benthic organisms which are susceptible to perturbation and exploitation, lend to the marine ecosystem in Glacier Bay is a great unknown. The role of these potentially impacted species in the complex web of this marine ecosystem should be one of Park Service's highest research priorities.

BIBLIOGRAPHY

Alaska Trollers Association 1977. Southeast Alaska Troll Log Book Program. 1976 Scientific Rept. Sea Grant Rept. 77-11. 61pp.

Anonymous 1963. Inventory of the Fishery of the Streams & Lakes of Glacier Bay National Monument. A.D.F.&G. Unpublished.

Anonymous 1970. Alaska NMFS Exploratory Fishing Drags.

Apollonio, S. 1973. Glaciers and Nutrients in Arctic Seas. Science 180:491-493.

Barnes, C.A. 1956. Oceanography of Silver Bay. University of Washington. Special Rept. No 24. Seattle, Washington. 60 pp.

Barr, L. 1970. Alaska's Fishery Resources: The Shrimps. Fish & Wildlife Service, B.C.F. Fishery Leaflet 631. 10 pp.

Bell, F.H. and G. St. Pierre 1970. The Pacific Halibut. Inter. Pacific Halibut Commission. Tech. Rept. No 6. 24 pp.

Benson, C., G. Wendler and R. March 1978. A Reconnaissance Investigation of the Air Pollution Potential in Glacier Bay National Monument; A Summary of the 1977 Field Season. Draft Manuscript to the National Park Service, Pacific Northwest Region.

Benson, C., G. Wendler and R. March 1977. A Reconnaissance Investigation of the Air Pollution Potential in Glacier Bay National Monument. Final Rept., CX-9000-6-0035. Alaska Cooperative Park Studies Unit. University of Alaska, Fairbanks.

Bohem, W.D. 1975. Glacier Bay: Old Ice, New Land. Alaska Geographic 3(1):1-134.

Bohn, D. 1967. Glacier Bay The Land and the Silence. Sierra Club. 160 pp.

Brooks, J.W. 1978. Status of Marine Mammal Stocks in Alaska. Presented at the 29th Alaska Science Conf. University of Alaska, Aug. 17, 1978.

Bruce, H.E., D.R. McLain and B.L. Wing 1977. Annual Physical and Chemical Oceanographic Cycles of Auke Bay, Southeastern Alaska. NOAA Tech. Rept. NMFS SSRF - 712. 11 pp.

Bruce, H.E. 1969. The Role of Dissolved Amino Acids as a Nitrogen Source for marine phytoplankton in an Estuarine Environment in Southeastern Alaska 1969. Ph.D. dissertation Oregon State University, Corvalis, Oregon. 124 pp.

Burrell, D.C. 1973. Distribution Patterns for Some Particulate and Dissolved Trace Metals within an active glacial Fjord. pp. 89-103. In *Radioactive Contamination in the Marine Environment* International Atomic Energy Agency, Vienna.

Burrell, D.C. 1971. Suspended Sediment Distribution Patterns within an Arctic Turbid - Outwash Fjord. pp. 227-245. In *Proceedings from the First International Conference on Port and Ocean Engineering under Arctic Conditions*. Vol 1.

Burrell, D.C. and R.S. Hadley 1971. The Liquid - Solid Distribution of Zinc across a Freshwater - Marine Interface. pp. 50-73. In *Trace Metal Associations in Sub-Arctic and Arctic Marine Environments, Work Completed 1970*. D.C. Burrell ed. Partial Progress Rept. for 1970-1971 to the U.S.A.E.C. Contract AT (45-1) - 2229 TA No 1.

Burrell, D.C. and C.M. Hoskin 1970. Cyclic Sedimentation Patterns within active glacial fjords. pp. 21-28. In *Clay-Metal Associations in Subarctic and Arctic Marine Environments*. D. Burrell ed. Partial Progress Rept. for 1969-1970 to the U.S.A.E.C. Contract AT(04-3) - 310 PA No 3.

Burrell, D.C., C.H. Hoskin and D.H. Rosenberg 1967. Geochemical and Marine Geological Investigations of Glacier Bay Fjords. Preliminary Data. pp. 13-40. In *Clay-Inorganic and Organic-Inorganic Associations in Aquatic Environments*. D.W. Hood & D.C. Burrell, eds. Progress Rept. to the AEC Contract AT(04-3) - 310. PA No 3.

Burrell, D.C. and J.B. Matthews 1974. Glacial Fjords. pp. 1-10, In *Coastal Ecosystems of the United States*. Vol III. H.T. Odum, B.J. Copeland and E.A. McMahan, eds. The Conservation Foundation. Washington, D.C.

Burrell, D.C. and N.R. O'Brien 1970. Some Geochemical Characteristics of Recent Glacial Sediments. Geochemical Journal 4:1-13.

Burrell, D.C., N.R. O'Brien and G.D. Sharma 1968. Geochemical and Mineralogical Investigations of Sediments Within an Active Glacial Fjord (abstract). Trans. Amer. Geophysical Union 49:367.

Calvin, N.I. 1977. A Qualitative Description of the Intertidal Plants and Animals of Berners Bay, Southeastern Alaska. Syesis 10:11-24.

Carlson, H.R., R.E. Haight and K.J. Krieger 1977. Species Composition and Relative Abundance of Demersal Marine Life In Waters of Southeastern Alaska, 1969-77. Northwest and Alaska Fisheries Center Processed Rept. Seattle, Washington. 69 pp.

Chang, J.C. 1971. An Ecological Study of Butter-Clam *(Saxidomus giganteus)* toxicity in Southeast Alaska. M.S. Thesis, University of Alaska. College, Alaska. 94 pp.

Dames and Moore 1976. Marine Plant Community Studies, Kachemak Bay, Alaska. Final Rept. for Alaska Dept. of Fish & Game, Job No 6791-003-20. Anchorage, Alaska. 288 pp.

Druehl, L.D. 1970. The Pattern of Laminariales Distribution in the Northeast Pacific. Phycologia 9(3/4):237-247.

Duggins, D.O. 1977. The Intertidal Zone of Bartlett Cove. Unpublished manuscript, National Park Service, Glacier Bay National Monument.

Duggins, D.O. and J.F. Quinn 1977. Keystone Predator and Marine Community Structure. pp. 95-106. In Dixon Harbor Biological Survey. G.P. Streveler and I.A. Worley, eds. National Park Service. Juneau, Alaska.

Dunbar, M.J. 1954. Arctic and Subarctic Marine Ecology. Arctic 7(3/4):213-228.

Ellson, J.G. and R.L. Livingston, Jr. 1952. The John N. Cobb's Shellfish Explorations in certain S.E. Alaskan Waters, Spring 1951. Com. Fish. Rev. 14(4):1-20.

Feder, H.M. et al. 1976. The Sediment Environment of Port Valdez, Alaska. The Effect of Oil on This Ecosystem. EPA Rept. - 600/3-76-86. Corvallis, Oregon. 321 pp.

Feder, H.M., G. Mueller, M. Dick and D. Hawkins 1973. Preliminary Benthos Survey. pp. 305-386. In D.W. Hood, W.E. Shiels and E.J. Kelley, eds. Environmental Studies of Port Valdez. Inst. Mar. Sci., University of Alaska Occas. Publ. No 3. 495 pp.

Forrester, J.W. 1968. Principles of systems. Wright-Allen Press. Cambridge, Mass. 384 pp.

Forrester, J.W. 1971. World dynamics. Wright-Allen Press. Cambridge, Mass. 142 pp.

Gallucci, V.F. 1978. Report on Bartlett Cove - Glacier Bay Clam-Related Ecosystem. Unpublished report to the National Park Service, Glacier Bay. 6 pp.

Gilmartin, M. 1964. The Primary Production of a British Columbia Fjord. J. Fish. Res. Bd. Canada. 21(3):505-538.

Goering, J.J., W.E. Shiels and C.J. Patton 1973. Primary Production. pp. 253-279. In Environmental Studies of Port Valdez. D.W. Hood, W.E. Shiels and E.J. Kelley, eds. Inst. Mar. Sci., University of Alaska Occas. Publ. No 3. 495 pp.

Goldthwait, R.P. and G.D. McKenzie 1977. Research by the Institute of Polar Studies in Glacier Bay National Monument, Alaska. Institute of Polar Studies Contribution No 315. The Ohio State University, Columbus. 23 pp.

Hadley, R.S. and D.C. Burrell 1971. Size Fractionation of Suspended Sediment in Queen Inlet. pp. 31-42. IMS Rept. No R71-12. Partial Progress Rept. for 1970-71 to the U.S. A.E.C. Contract AT(45-1) - 2229, TA No 1.

Hadley, R.S. and D.C. Burrell 1970. Glacial Sediment Cyclic Black Layer. pp. 17-18. D. Burrell, ed. Progress Report to U.S. Atomic Energy Commission, Contract No AT(04-3) - 310 PA No 3.

Hartman, W.L. 1971. Alaska's Fishery Resources, The Sockeye Salmon. NOAA, NMFS Fishery Leaflet 636. Seattle. 8 pp.

Haven, S.B. 1971. Effects of Land-level changes on intertidal invertebrates, with a discussion of post earthquake ecological succession. pp. 82-126. In The Great Alaska Earthquake of 1964. National Academy of Sciences. Washington, D.C. 287 pp.

Heggie, D.T. 1972. Observations of Gases in Sediments of Alaskan Aquatic Environments. M.S. Thesis. University of Alaska. College, Alaska.

Hoopes, D. T. 1973. Alaska's Fishery Resources - The Dungeness Crab. Fishery Facts - 6. NMFS Extension Publication. Seattle, Washington. 14 pp.

Hoskin, C.M. 1977. Macrobenthos from three Fjords in Western Prince William Sound, Alaska. IMS Rept. 77-1. University of Alaska. College, Alaska. 28 pp.

Hoskin, C.M., D.C. Burrell and G.R. Freitag 1976. Suspended Sediment Dynamics in Queen Inlet, Glacier Bay, Alaska. Mar. Sci. Communications 2(2):95-108.

Hoskin, C.M. and D.C. Burrell 1972. Sediment Transport and Accumulation in a Fjord Basin, Glacier Bay, Alaska. Journal of Geology. 80:539-551.

Hoskin, C.M. and G.J. Mueller 1977. Dynamics of Sediment Transport by Ice Rafting & Sediment Macrobenthos Interactions, Muir Inlet, Glacier Bay National Monument, Alaska. Proposal to NSF.

Hubbard, J.D. 1971. Distribution and Abundance of Intertidal invertebrates at Olsen Bay in Prince William Sound, Alaska, one year after the 1964 earthquake. pp. 137-157. In The Great Alaska Earthquake of 1964. National Academy of Science, Washington, D.C.

Imler, R.H. and H.R. Sarber 1947. Harbor Seals and Sea Lions in Alaska. U.S. Fish & Wildlife Service. Special Scientific Rept. No 28. 23 pp.

International Pacific Halibut Commission 1978. The Pacific Halibut: Biology, Fishery and Management. Technical Rept. No 16. Seattle, Washington. 56 pp.

Jettmar, K. and C. Summers 1975. Glacier Bay: Wilderness or Mining Boom? Nat'l Parks & Conservation Mag. 49(5):6-11.

Jurasz, C. and V. Jurasz 1978. Results of 1977 Studies on Humpback Whales in Glacier Bay National Monument. Final Rept. CX-9000-7-0045. Cooperative Park Studies Unit. University of Alaska, Fairbanks.

Jurasz, C.M. and V. Jurasz 1977. Status of Humpback Whales and other Cetacea in Glacier Bay National Monument. Final Rept. CX-9000-6-0085. Alaska Cooperative Park Studies Unit. University of Alaska, Fairbanks.

Kenyon, K.W. 1952. Notes on the food of fur seal, sea lion and harbor porpoise. J. of Wildlife Mgnt. 16(3):396-397.

Laevastu, T. and F. Favorite 1977. Preliminary Rept. on Dynamical Numerical Marine Ecosystem Model for Eastern Bering Sea. NMFS, Seattle, Washington. 81 pp.

Lawrence, D.B. 1958. Glaciers and Vegetation in Southeastern Alaska. Amer. Sci. 46(2):89-122.

Loder, T.C. III 1971. Distribution of Dissolved and Particulate Organic Carbon in Alaskan Polar, Sub-Polar and Estuarine Waters. Ph.D. Thesis. University of Alaska. College, Alaska. 236 pp.

Loder, T.C. and D.W. Hood 1972. Distribution of Organic Carbon in a Glacial Estuary in Alaska. Limnol. Oceanog. 17(3):349-355.

Longerich, L.L., M. Billington, V. Alexander, J.J. Kelley and D.W. Hood 1971. Carbon Dioxide and Primary Productivity in the Glacial Fjord System of Southeast Alaska. IMS Rept. R71-19, University of Alaska. College, Alaska. 19 pp.

MacKevett, E.M., D. Brew, C.C. Hawley, L.C. Huff and J.G. Smith 1967. Mineral Resources of Glacier Bay National Monument. Alaska Geological Survey Professional Paper 632. 90 pp.

McRoy, P. 1970. Standing Stocks and other Features of Ellgrass (_Zostera marina_) populations on the coast of Alaska. J. Fish Res. Bd. Canada, 27:1811-1821.

McRoy, C.P. 1974. Bird and Mammal Island Subsystems of Higher Latitudes. pp. 30-47. In H.T. Odum, B.J. Copeland and E.A. McMahan, eds. Coastal Ecological Systems of the U.S. Vol III. The Conservation Foundation.

McRoy, C.P., J.J. Goering, M.T. Grottschalk, M. Mueller, S. Stoker 1971. Survey of Macrophyte Resources in the Coastal Waters of Alaska. IMS Rept. R71-6. University of Alaska. College, Alaska. 40 pp.

Matthews, B. unpublished manuscript. The Seasonal Circulation of the Glacier Bay, Alaska Fjord System. University of Alaska, College.

Matthews, J.B. 1971. Some Aspects of the Hydrography of Alaskan and Norwegian Fjords. Proceedings from the First International Conf. on Port and Ocean Eng. under Arctic Conditions. 1:829-839.

Matthews, J.B. and A.V. Quinlan 1975. Seasonal Characteristics of Water Masses in Muir Inlet, a Fjord with Tidewater Glaciers. J. Fish. Res. Bd. Canada. 32:1693-1703.

Mattson, C.R. and B. Wing 1978. Icthyoplankton Composition and Plankton Volumes from Inland Coastal Waters of Southeastern Alaska, April - November 1972. NOAA Tech. Rept. NMFS SSRF-723. 11 pp.

Merrell, T.R., Jr. 1970. Alaska's Fishery Resources. The Chum Salmon. USF&WS. B.C.F., Fishery Leaflet 632. 7 pp.

Millner, S. 1978. Unpublished Rept. to the National Park Service, Glacier Bay National Monument, Bartlett Cove.

Mueller, G. 1973. Preliminary Survey of Intertidal Fauna and Flora of Glacier Bay National Monument: A Final Rept. Unpublished M.S. National Park Service, Glacier Bay National Monument, Bartlett Cove.

Mueller, G., A.S. Naidu and D. Schamel 1977. Benthic Marine Studies. pp. 66-94. In Dixon Harbor Biological Survey. G.P. Streveler and I.A. Worley, eds. National Park Service, Juneau, Alaska.

Myhre, R.J., G.J. Peltonen, G. St. Pierre, B.E. Skud, and R.E. Walden 1977. The Pacific Halibut Fishery: Catch, Effort and CPUE, 1929-1975. International Pacific Halibut Com. Tech. Rept. No 14. Seattle, Washington. 95 pp.

Naidu, A.S. and D.M. Triplehorn 1971. Lithology and Chemical Character of fiordal sediments, Southeastern Alaska. pp. 52-54. In IMS Rept. No R71-12. Partial Progress Report for 1970-71 to the USAEC. Cont AT(45-1) - 2229, TA 1.

Nybakken, J.W. 1969. Pre-earthquake Intertidal Ecology of Three Saints Bay, Kodiak Island, Alaska. Biol. Papers of the University of Alaska. No 9. 117 pp.

O'Brien, N.R. and D.C. Burrell 1970. Mineralogy and Distribution of Clay Size Sediment in Glacier Bay, Alaska. Journal of Sed. Petrology, 40(2):650-655.

Odum, E.P. 1971. Fundamentals of ecology. W.B. Saunders Co. Philadelphia. 574 pp.

Ovenshine, D.T. 1970. Observations of Iceberg Rafting in Glacier Bay, Alaska, and the Identification of Ancient Ice Rafted Deposits. Geol. Soc. Am. Bull. 81:891-894.

Patten, S.M. 1974. Breeding Ecology of the glaucous winged gull (Larus glaucescens) in Glacier Bay, Alaska. M.S. Thesis, University of Washington, Seattle. 78 pp.

Patten, S. and A.R. Weisbrod 1974. Sympatry and Interbreeding of Herring and Glaucous-Winged Gulls in Southeastern Alaska. The Condor 76(3):343-344.

Paul, A.J. and H.M. Feder 1976. Clam, Mussel and Oyster Resources of Alaska. Inst. of Marine Science Rept. 76-4. University of Alaska, College. 41 pp.

Pickard, G.L. 1967. Some Oceanographic Characteristics of the Larger Inlets of Southeast Alaska. J. Fish. Res. Bd. Canada. 24(7):1475-1506.

Pierce, C. 1960. Is Sea Level Falling or the Land Rising in S.E. Alaska. Presentation at 20th Annual Meeting American Congress in Surveying and Mapping. March 20-23, 1960. Washington, D.C.

Pitcher, K. and D. Calkins 1978. Biology of the Harbour Seal, Phoca virtulina richardi in the Gulf of Alaska. ADF&G. Annual Rept. 1 April 1977 - 31 March 1978. Cont. 03-5-022-69.

Pitcher, K. 1977. Population Productivity and Food Habits of Harbor Seals in the Prince William Sound - Copper River Delta area, Alaska. ADF&G Rept. No MMC-75/03. 36 pp.

Post, A. and E.R. LaChapelle 1971. Glacier Ice. The Mountaineers, Seattle. 110 pp.

Quinlan, A.V. 1970. Seasonal and Spatial Variations in the Water Mass Characteristics of Muir Inlet, Glacier Bay, Alaska. M.S. Thesis University of Alaska. College, Alaska. 145 pp.

Quast, J.C. and E.L. Hall 1972. List of Fishes of Alaska and Adjacent Waters with a Guide to Some of their Literature. NOAA Technical Report NMFS SSRF-658. Seattle, Washington. 47 pp.

Quinn, J.F. and D.O. Duggins 1977. Rocky Intertidal Communities. pp. 107-125. In Dixon Harbor Biological Survey. G.P. Streveler and I.A. Worley, eds. National Park Service, Juneau.

Rae, K.M. and L.I. Knowles 1965. Ecological Implications of Clay-Metal Associations in Aquatic Environments. Progress Rept. to AEC (Mar. 1964 - Apr. 1965) AEC Contract AT(04-3) - 310. Ref: Inst. of Mar. Sci. 65-4.

Reid, G.M. 1961. Stomach Content Analysis of Troll-Caught King and Coho Salmon, Southeastern Alaska, 1957-58. USF&WS Spec. Sci. Rept. Fisheries No 379. 8 pp.

Reid, G.M. 1972. Fishery Facts - 2 Alaska's Fishery Resources---the Pacific Herring. NMFS Extension Publication. Seattle, Washington. 20 pp.

Rich, P. and A.R. Tussing 1973. The National Park System in Alaska: An Economic Impact Study. Institute of Social, Economic and Government Research. University of Alaska. College, Alaska. 88 pp.

Robards, F.C. and J.G. King 1966. Nesting and Productivity of Bald Eagles - Southeast Alaska-1966. U.S. Dept. of the Interior. Bureau of Sport Fisheries and Wildlife. Juneau, Alaska. 14 pp.

Ronholt, L.L. 1963. Distribution and Relative Abundance of Commercially Important Pandalid Shrimps in the NE Pacific Ocean. U.S. Fish & Wildlife Service. Special Scientific Rept. Fisheries No 449. 28 pp.

Rosenberg, D.H., ed. 1972. A Review of the Oceanography and Renewable Resources of the Northern Gulf of Alaska. University of Alaska, Institute of Marine Science Rept. 72-23. 690 pp.

Rossman, D.L. 1958. Geology and Ore Deposits, Reid Inlet area, Glacier Bay, Alaska. With notes on a mineralized area near Lituya Bay. Geol. Survey Bulletin 1058-B. 59 pp.

Rounsefell, G.A. and E.H. Dahlgren 1935. Races of herring, Clupea pallasii in Southeastern Alaska. U.S. Dept. of Commerce, Bureau of Fisheries Bulletin No 17. pp. 119-141.

Sanger, G., V.F. Hironaka and A.K. Fukuyama 1978. The feeding ecology and trophic relationships of key species of marine birds in the Kodiak Island area, May-Sept. 1977. U.S. Fish & Wildlife Service. NOAA-OCSEAP Contract: 01-5-022-2538. Annual Rept.

Selkregg, L.L. 1976. Alaska Regional Profiles, Southeast Region. A.E.I.D.C., University of Alaska. 233 pp.

Sharma, G.D. 1966. Depositional environments and sediments in Southeastern Alaska. Presented at the 17th Alaskan Science Conf. Anchorage, Alaska. August 1966.

Sharma, G.D. 1970. Productivity and Chemical Cycling of Silica in Southeast Alaska. pp. 27-32. In Proceedings Interocean '70. Vol II. VDI-Verlag, Dusseldorf, West Germany.

Sharma, G.D. 1970. Sediment-Seawater Interaction in Glaciomarine Sediments of Southeast Alaska. Geol. Soc. of Amer. Bull. 81:1097-1106.

Skud, B.E. 1959. Herring Spawning Surveys in Southeastern Alaska. USF&WS. Special Scientific Rept. Fisheries No 321. 16 pp.

Smith, N.C. 1972. Intertidal Communities of Berners Bay, Alaska. M.S. Thesis, Western Washington State College, Bellingham, Washington. 72 pp.

Streveler, G.P. 1978. Harbor Seal Studies in Glacier Bay, Alaska. Progress Rept. to the National Park Service. Unpublished Rept. Juneau, Alaska.

Streveler, G.P. and B.B. Paige 1971. The Natural History of Glacier Bay National Monument, Alaska. A Survey of Past Research and Suggestions for the Future. National Park Service, Glacier Bay National Monument, Bartlett Cove. 89 pp.

Thorsteinson, F.V. 1962. Herring predation on pink salmon fry in a Southeastern Alaska estuary. Trans. Am. Soc. Fish. 91(3):321-323.

U.S.D.O.I., Fish and Wildlife Service. Bureau of Com. Fish. 1967. Cruise Rept. M/V John R. Manning Alaska Exploratory Cruise. 66-4. Oct. 31 - Dec. 16, 1966.

U.S.D.O.I., National Park Service. 1979. Environmental consequences of mineral extraction: Glacier Bay National Monument and Mount McKinley National Park. Report to Congress. 123 p.

Wallen, D.D. and D.W. Hood 1968. Descriptive Oceanography of Alaskan Waters/Chem. of Marine Interfaces. Progress Rept. to the office of Naval Research Contract No NONR 3010(05). Inst. Mar. Sci., University of Alaska. 114 pp.

Wik, D. 1967. Birds of Glacier Bay National Monument. National Park Service, unpublished manuscript. Glacier Bay National Monument, Bartlett Cove.

Williamson, R. 1974. Phytoplankton Species and their Geographical Distribution in Southeast Alaska. NMFS, Auke Bay Fisheries Laboratory Manuscript Rept. File No 112.

Wing, B. 1978. Intertidal biota collected during comparative estuarine studies project---Fishes (CESP-FISH) April 1967 - April 1968. NMFS Manuscript Rept. - File No 144.

Wing, B.L. and G.M. Reid 1972. Surface Zooplankton from Auke Bay and Vicinity, Southeastern Alaska. Aug. 1962 - Jan 1967. NOAA, NMFS Data Rept. 72.

Wright, F.F. and G.D. Sharma 1969. Preglacial Marine Sedimentation in Southern Alaska. pp. 179-185. In Proceedings of the VIII^{e} Congres I.N.Q.U.A., Paris.

Wright, F.F. 1971. Fjord Circulation and Sedimentation, Southeast Alaska. Procd. from the first International Conf. on Port and Ocean Engineering under Arctic Conditions. 1:279-284.

APPENDIX I

PERSONS FROM WHOM VERBAL INFORMATION WAS OBTAINED

Dr. Carl S. Benson, Geophysical Institute, University of Alaska

Dr. David C. Burrell, Institute of Marine Science, University of Alaska

Dr. Natasha Calvin, Auke Bay Laboratory, National Marine Fisheries Service

Dr. Frederick Dean, Cooperative Park Studies Unit, University of Alaska

Peter Donau, Manager, Glacier Bay Lodge

David Duggins, Cooperative Park Studies Unit, University of Washington

Dr. Vincent F. Gallucci, University of Washington

Charles Jurasz, Whale Researcher, Juneau

Virginia Jurasz, Whale Researcher, Juneau

Chuck Kearns, Charter Boat Captain, Glacier Bay Lodge

Dr. Peter C. McRoy, Institute of Marine Science, University of Alaska

Dr. J. Brian Matthews, Geophysical Institute, University of Alaska

George J. Mueller, Seward Marine Laboratory, University of Alaska

David L. Nebert, Institute of Marine Science, University of Alaska

Bruce B. Paige, Park Naturalist, Glacier Bay National Monument

Dr. Jay Quast, Auke Bay Laboratory, National Marine Fisheries Service

Richard Ried, Chief, Habitat Protection, Southeast Alaska, Alaska Department of Fish and Game

Thomas Ritter, Superintendent, Glacier Bay National Monument

Dr. Ghanshyman D. Sharma, Institute of Marine Science, University of Alaska

Frederick Short, Institute of Marine Science, University of Alaska

Gregory P. Streveler, Research Biologist, Glacier Bay National Monument

Dr. Bruce Wing, Auke Bay Laboratory, National Marine Fisheries Service

APPENDIX II

DATA APPENDIX

TABLE OF CONTENTS

TITLE — ITEM NUMBER

CLIMATE

Sky Cover: May, June, July, August, September 1976, 1977 1

HYDROGRAPHIC DATA

R.V. Acona hydrographic stations in Glacier Bay 2
Longitudinal profiles of salinity, temperature, density anomoly and dissolved oxygen in Muir Inlet at four times of the year 3
Mean seasonal profile of density anomoly, dissolved oxygen, temperature and salinity in lower Glacier Bay 4
Hydrographic data from Queen Inlet 5
Surface-water temperature and salinity in Glacier Bay 6
Characteristic vertical profiles of temperature, salinity and dissolved oxygen in Glacier Bay 7

NUTRIENTS

Nutrient data available for Glacier Bay 8
Nutrient data listings from RV Acona Cruises 9
Bartlett Cove nutrient data, 1969 10
Distribution of dissolved silica in Southeast Alaska, September 1965 - June 1966 11
Vertical profiles of dissolved silica for Glacier Bay, 1965 and 1966 12

INTERTIDAL ZONE

Intertidal sampling stations in Glacier Bay 13
Glacier Bay intertidal zone - Species List 14

PHYTOPLANKTON

Fluctuations of diatom and dinoflagellate populations in Bartlett Cove, 1968 - 1969 15

ZOOPLANKTON

Zooplankton counts: Lampu Glacier, 5 August 1963; Beardslee Islands, 7 August 1963 16

TABLE OF CONTENTS (cont.)

TITLE ITEM NUMBER

FISH

Alaska NMFS exploratory fishing drags: Glacier Bay station locations and catch 17
Shrimp trawl catch: Icy Strait 18

BIRDS

Preferred locations of common birds in Glacier Bay 19*

COMMERCIAL FISHING

Halibut catch, C.P.U.E. and effort for I.P.H.C. Area 182, 18 S-I, and all of southeast Alaska 20
Total salmon landings, A.D.F.&G. Area 114, 1971 - 1976 21
Total crab landings for Glacier Bay and A.D.F.&G. Area 114 22

VESSEL TRAFFIC

Annual patterns of vessel traffic in Glacier Bay 23
Classification of vessels in Glacier Bay, June 1977 24

MINING

Memo, Larry May, N.P.S., on impacts of mining in Glacier Bay 25

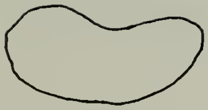
SEWAGE DISPOSAL

Federal marine sanitation device regulations 26*

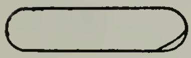
* in back cover pouch

APPENDIX III

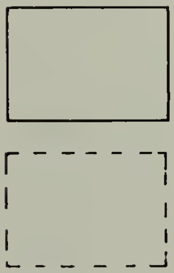
CONVENTIONS AND SYMBOLS USED IN THE MODEL DIAGRAMS



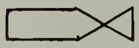
Source or Sink: Used to represent the point of origin or point of dispersal for the matter or energy which is flowi through the system, when this point is considered to lie outside the boundary of the model.



Driving Variable: Factors, principally climatic or abiotic in origin, which influence the system and which are not influenced by changes that occur within the system.



State Variable: The measureable components of the ecosystem under study, the factors of principal interest. In the submodels, two types of state variables are defined. The solid rectangles are components of the system under study, the dashed rectangles are components of systems which occur beyond the boundaries of Glacier Bay.



Process: These can best be thought of as valves that control the flows of matter or energy through the system. Common processes include predation and reproduction.

○	Auxiliary Variable: These include intermediate calculations which if the model was mathematical would be computed during the sequence of running the model.
—⊖—	Constant: These contain numerical values that describe the characteristics of the system or signify so-called normal values to be used in rate equations.
⟶	A direct flow of material or energy.
- - - ->	A flow of information. Unlike the direct flows, the take-off of an information flow does not affect the variable from which the information was taken.

APPENDIX IV

ABBREVIATIONS USED IN THE CONCEPTUAL ECOLOGICAL MODELS OF GLACIER BAY

ABBREVIATION	WORD
atm light	atmospheric light
avail food	available food
break	breakage
bot wat ren	bottom water renewal
cannib	cannibalism
D	death
decomp	decomposition
deglac	deglaciation
emmig	emmigration
glac melt	glacial meltwater
immig	immigration
MACROAL	macroalgae
MAR MAM	marine mammals
MEROPL	meroplankton
metamor	metamorphosis
new substr	new substrate
non plank pop	non-planktonic population
nut stat	nutritional status
P	predation

ABBREVIATION	WORD
photosyn	phtotsynthesis
PHYTOPL	photoplankton
psr	plankton sinking rate
repro	reproduction
sed rate	sedimentation rate
sep moth	separation from mother
sep sys	septic system
SM PEL FISH	small pelagic fish
STP	sewage treatment plant
susp. p.m.	suspended particulate matter
temp	temperature
terr sites	terrestrial sites
turb	turbidity
ZOOPL	zooplankton

☆GPO 1979-699-259

Clemson University
3 1604 004 717 684

DATE DUE

Demco, Inc. 38-293